From femtosecond to attosecond RF field control.

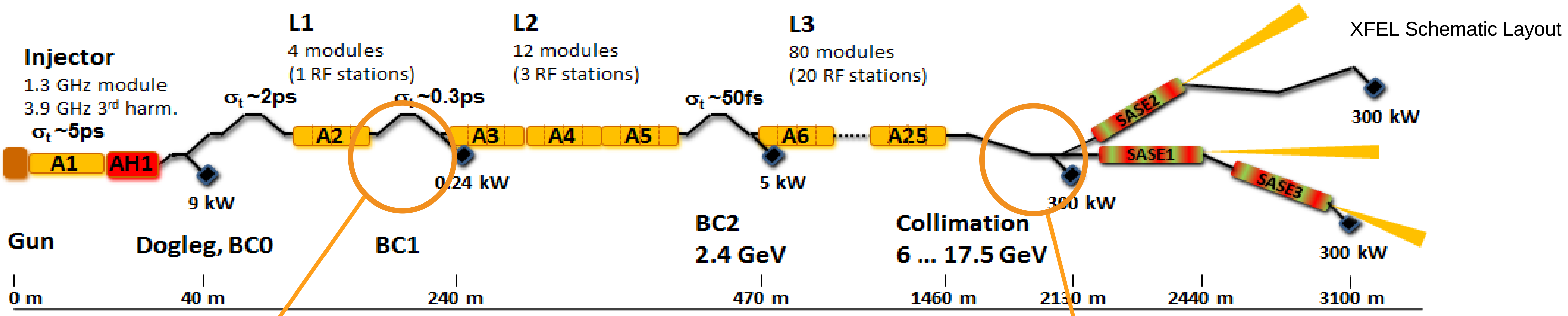
IPAC 2026, 17th International Particle Accelerator Conference

Dr. Frank Ludwig on behalf of the LLRF, LbSync, Special Diag. team at DESY
Deauville, Normandy, France, 22.05.2026

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Source of timing jitter for accelerators / FELs



- RF acceleration fields define arrival time:

Amplitude **Phase** **Init. arrival**

$$t_{j,\mathrm{out}}^2 \approx \left(\frac{R_{56}}{c_0}\frac{\sigma_A}{A}\right)^2 + \left(\frac{C-1}{C}\right)^2\left(\frac{\sigma_\varphi}{c_0 k_{\mathrm{rf}}}\right)^2 + \left(\frac{1}{C}\right)^2 t_{j,\mathrm{in}}^2$$

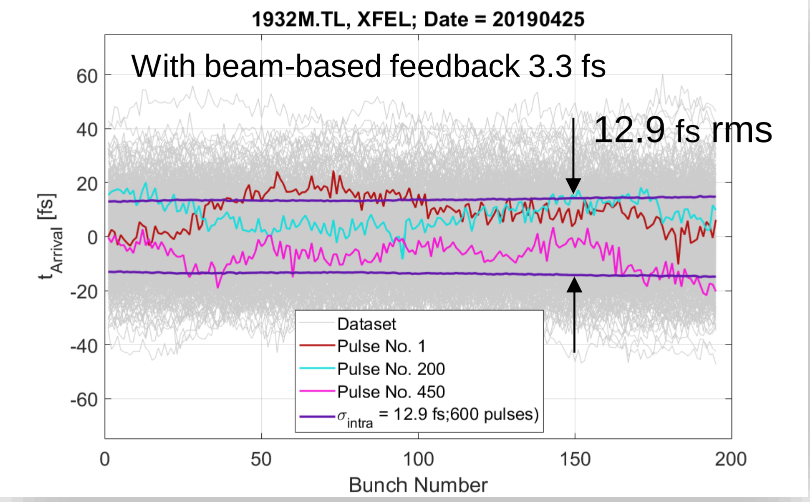
XFEL: 1.5ps/%
FLASH: 7.0ps/%

2 ps/deg
L-band

0.05 ps/ps
C=20

Conclusions for 10fs bunch arrival time:

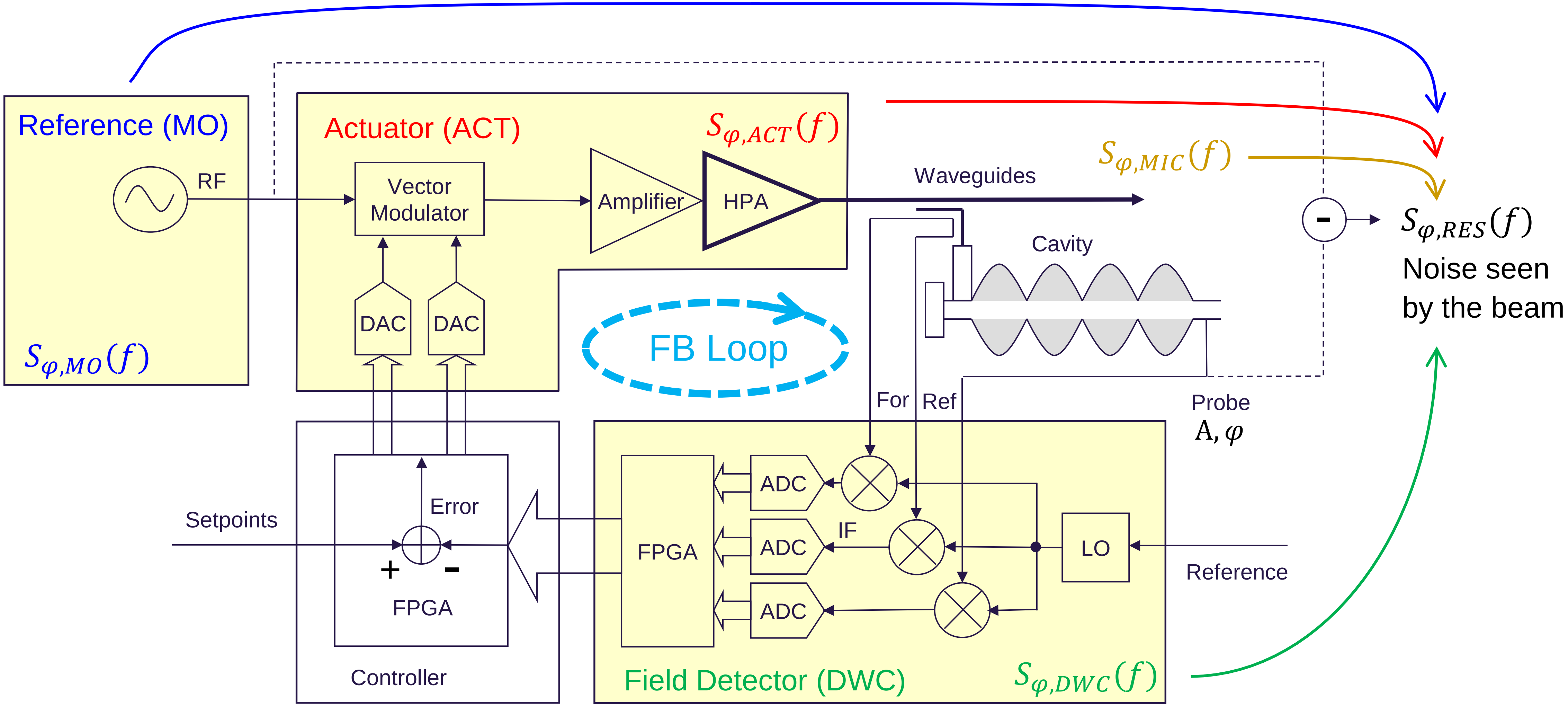
RF field control and reference distribution is critical <0.01%, <0.01deg @ 1.3GHz



Courtesy of H.Schlarb

Low-Level-Radio-Frequency (LLRF) Control

- High-frequency regulation – main noise sources: ACT, DWC, MO, MIC



Low-Level-Radio-Frequency (LLRF) Control

- Concept of envelope approach for AN, PN modelling (simplified):

$$S_{\varphi,RES}(f) = \left|\frac{s}{s+\omega'_{12}}\right|^2 S_{\varphi,MO}(f) + \left|\frac{\omega'_{12}}{s+\omega'_{12}}\right|^2 \left(S_{\varphi,DWC}(f) + \frac{1}{g_0^2} S_{\varphi,ACT}(f)\right) + \left|\frac{s+\ \omega_{12}}{s+\omega'_{12}}\right|^2 S_{\varphi,MIC}(f)$$

high-pass — low-pass — high- and low-pass

Cavity effective noise bandwidth $\omega'_{12} = g_0\, \omega_{12}$

Cavity field phase fluctuations *:

$$\sigma^2_{\varphi,RES} \approx K_{MO} \ln(2) + \left(g_0\, S_{\varphi,DWC} + \frac{1}{g_0}\, S_{\varphi,ACT}\right) \frac{\pi}{2}\, f_{12} + \frac{2}{(g_0\, f_{12}\,)^2} S_{\Delta f,MIC}\, \Delta f_{MIC}$$

Optimal gain — Optimal cavity bandwidth

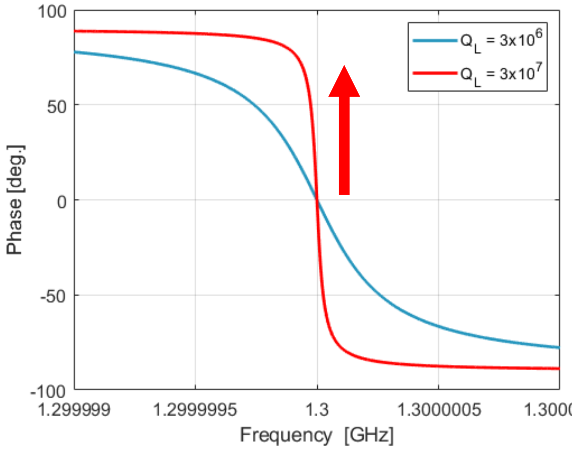
- The actuator and microphonic noise can be reduced by increasing the gain **.
- But the field detector noise must be very low.

Microphonics:

Detuning to phase conversion

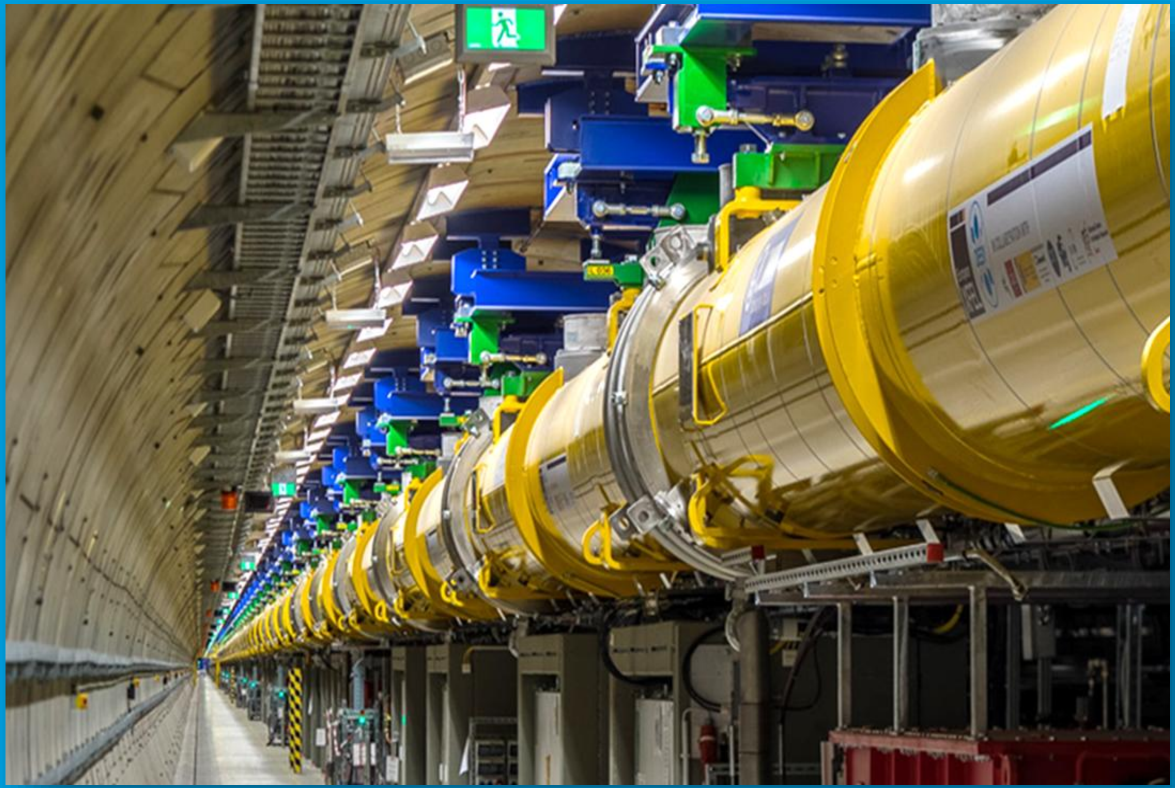
$$S_{\varphi,MIC}(f) = \left(\frac{2Q_L}{f_0}\right)^2 S_{\Delta f,MIC}(f)$$

$$S_{\varphi,MIC}(f) = \left(\frac{1}{f_{12}}\right)^2 S_{\Delta f,MIC}(f)$$



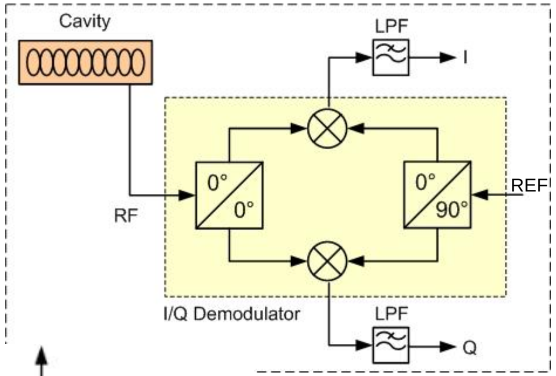
* MO with 1/f, DWC, ACT, MIC white noise behavior., ** limited by the system latency

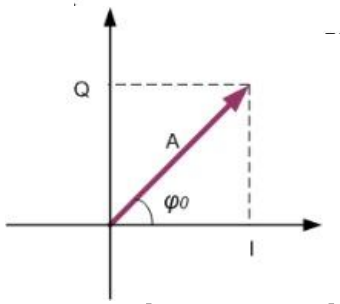
RF-Controls
with fs-Precision

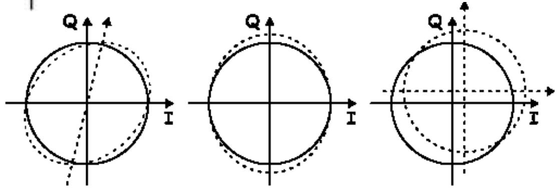


Field Detectors – Modulation Schemes

IQ-baseband Sampling:

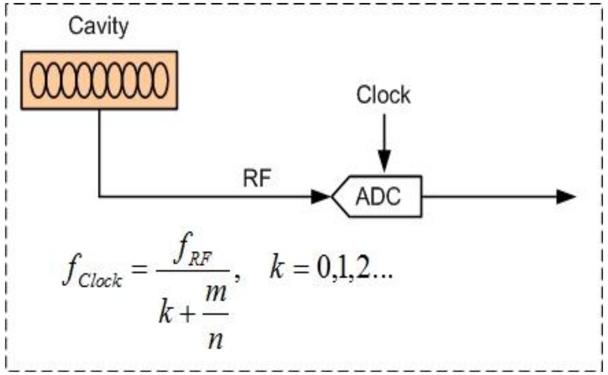






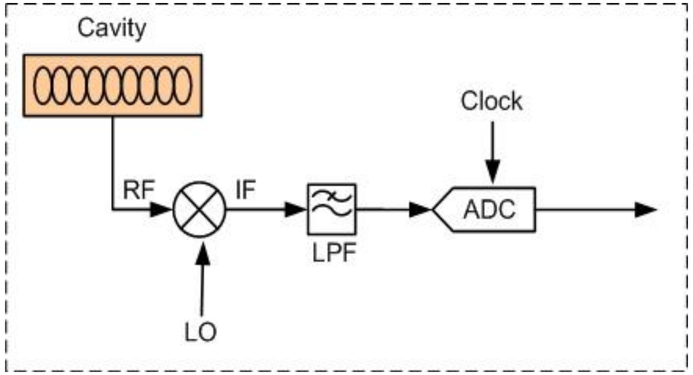
(+) No LO-Generation
(--) IQ-Errors in the % range
(--) PM to AM effects
(--) IQ-Calibration is needed

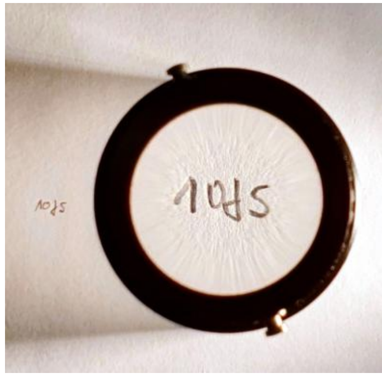
Direct Sampling:

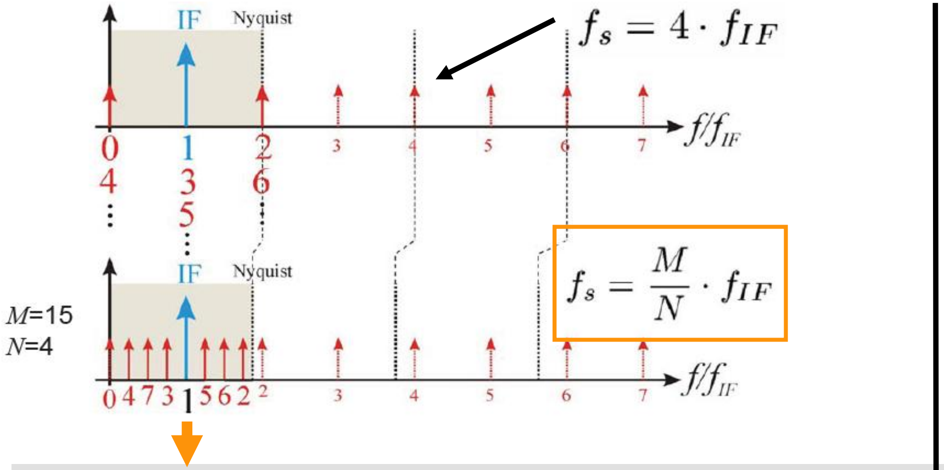


(+) Wideband, flexible use
(+) AM <0.01% @ 1.3GHz
( ) SNR sensitive to CLK jitter
due to high input frequency

Non-IQ Sampling (gold standard):

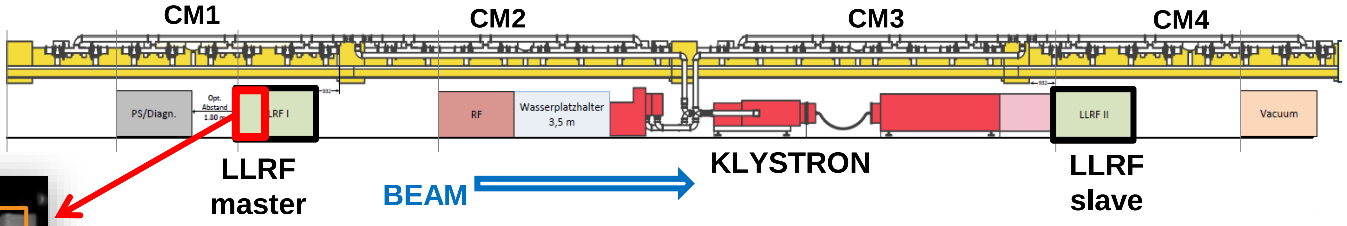






(+) Most harmonics do not alias into the signal
(+) No PM to AM effects
(+) Analog mixer ‘magnifies‘ the RF time jitter
(--) Requires mixer and LO-Generation

LLRF-Systems – European XFEL



- XFEL 48-channel LLRF station:

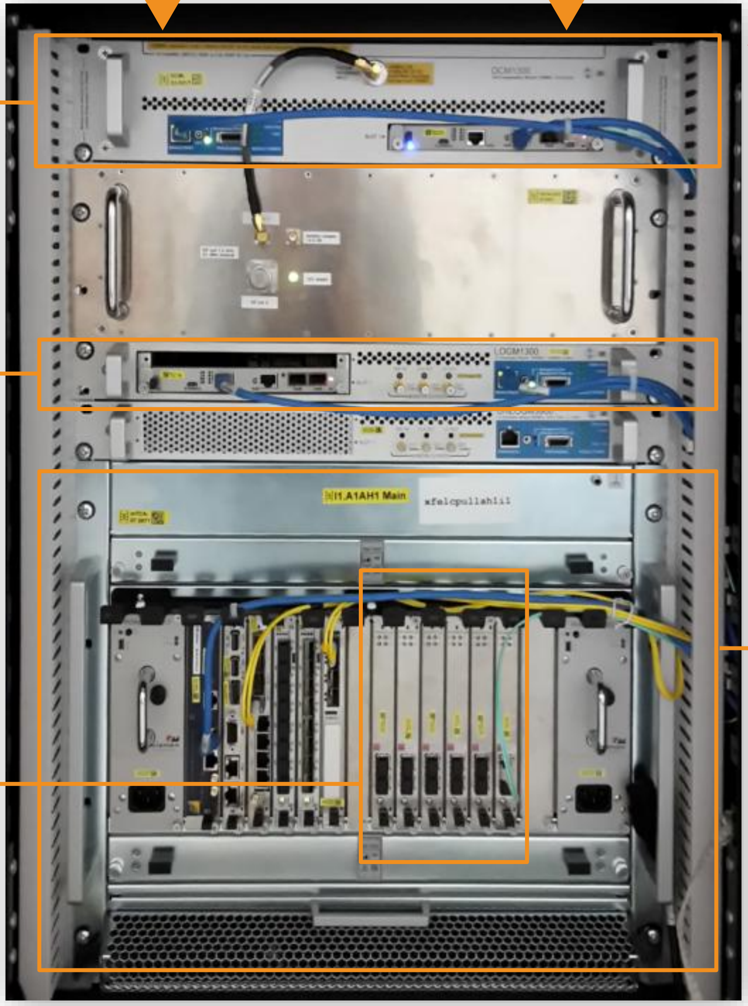
Cavity patch panel

Drift Compensation
(DCM, 2U 19")

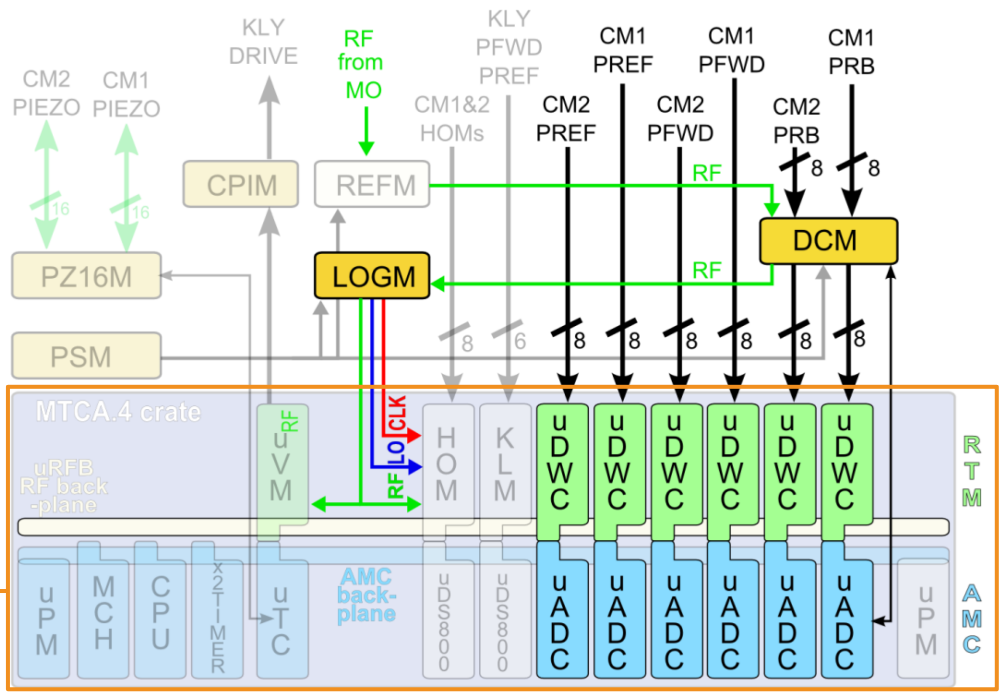
LO-Generation
(LOGM, 1U 19")

Down-Converter
(DWC, RTM)

Low-noise Digitizer
(ADC, AMC)



MicroTCA.4

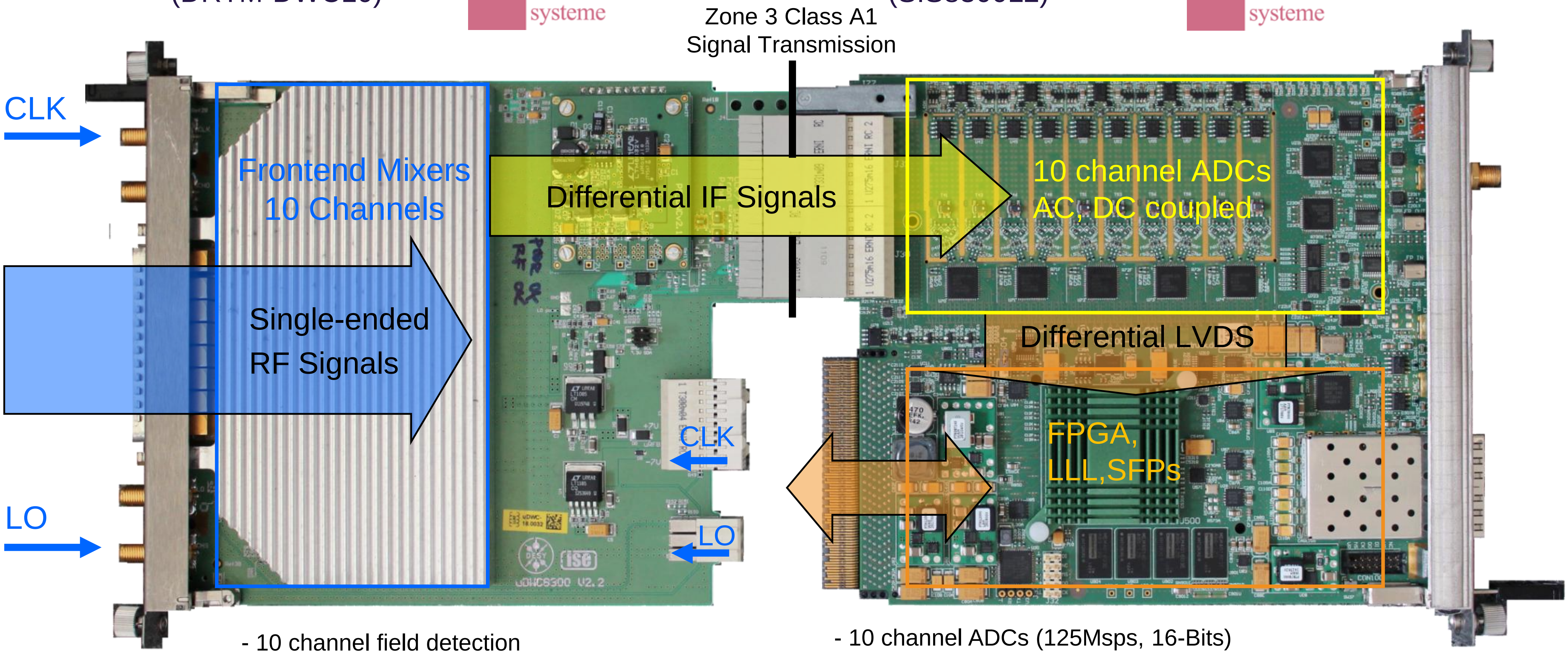


- MicroTCA.4 complete suite: LLRF/Diag./Interlocks/HOM

  Challenges:
- Total: 27 RF station / 800 cavities / >3000 RF signals
- Stability requirements < 0.01% & 0.01deg

LLRF-Systems – Signal Conditioning, Digital Processing

- High frequency Down-Converter (DRTM-DWC10) struck innovative systeme
- Multi-Channel fast ADC Digitizer (SIS8300L2) struck innovative systeme



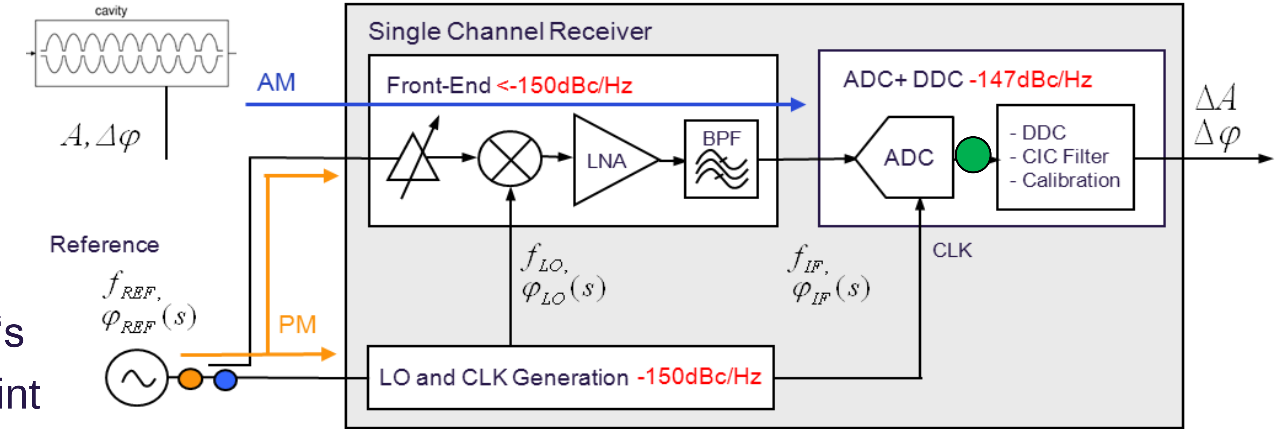
- 10 channel field detection
- S-band (700MHz - 4.0GHz)
- Resolution, 0.004%, < 10fs

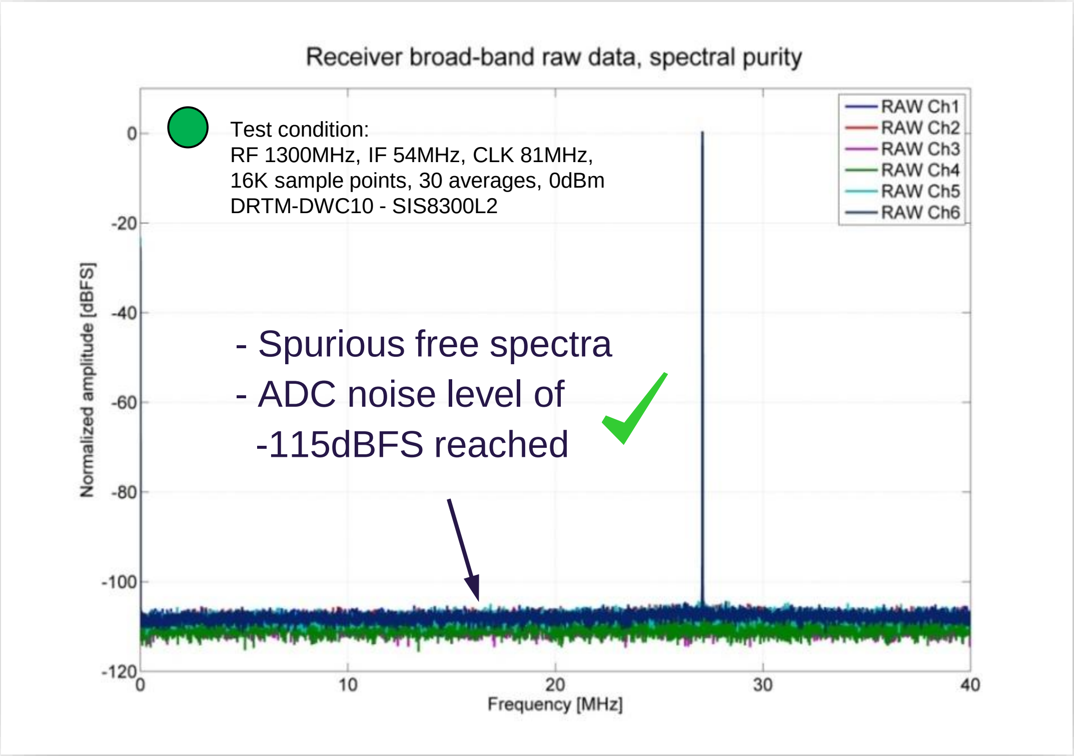
- 10 channel ADCs (125Msps, 16-Bits)
- FPGA (Virtex6) pre-processing partial cavity vectors
- Low latency links via MTCA-backplane

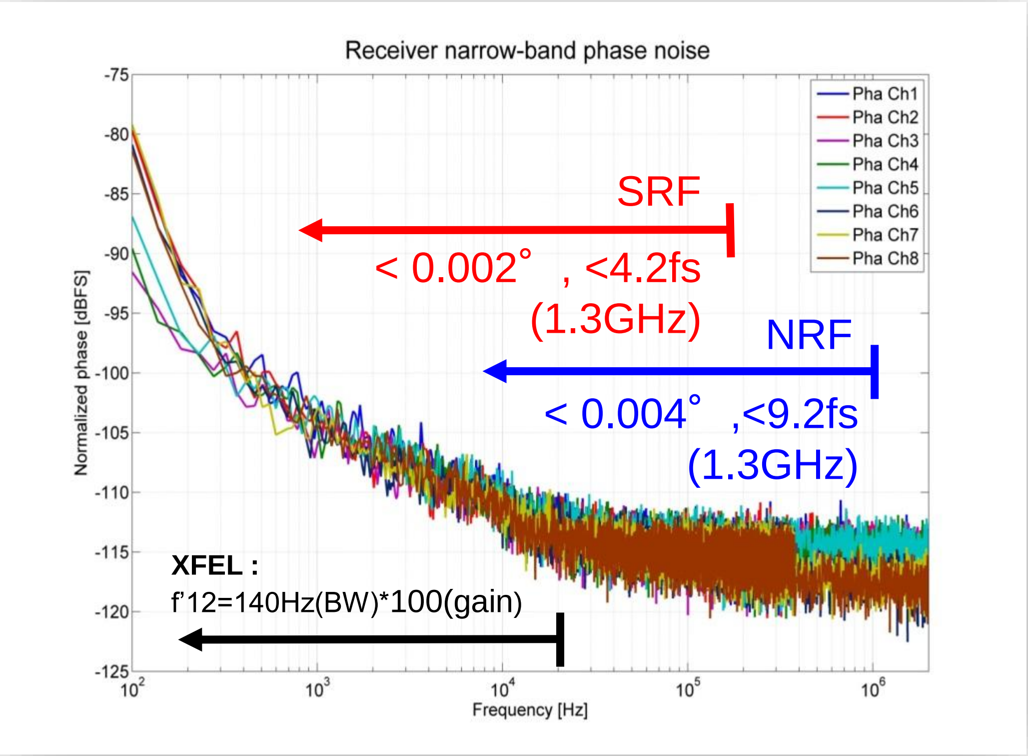
LLRF-Systems (<10fs) Channel Performance

- Spectral purity :
  (non-IQ Sampling scheme)
  - Mainly ADC limited

System‘s Fingerprint



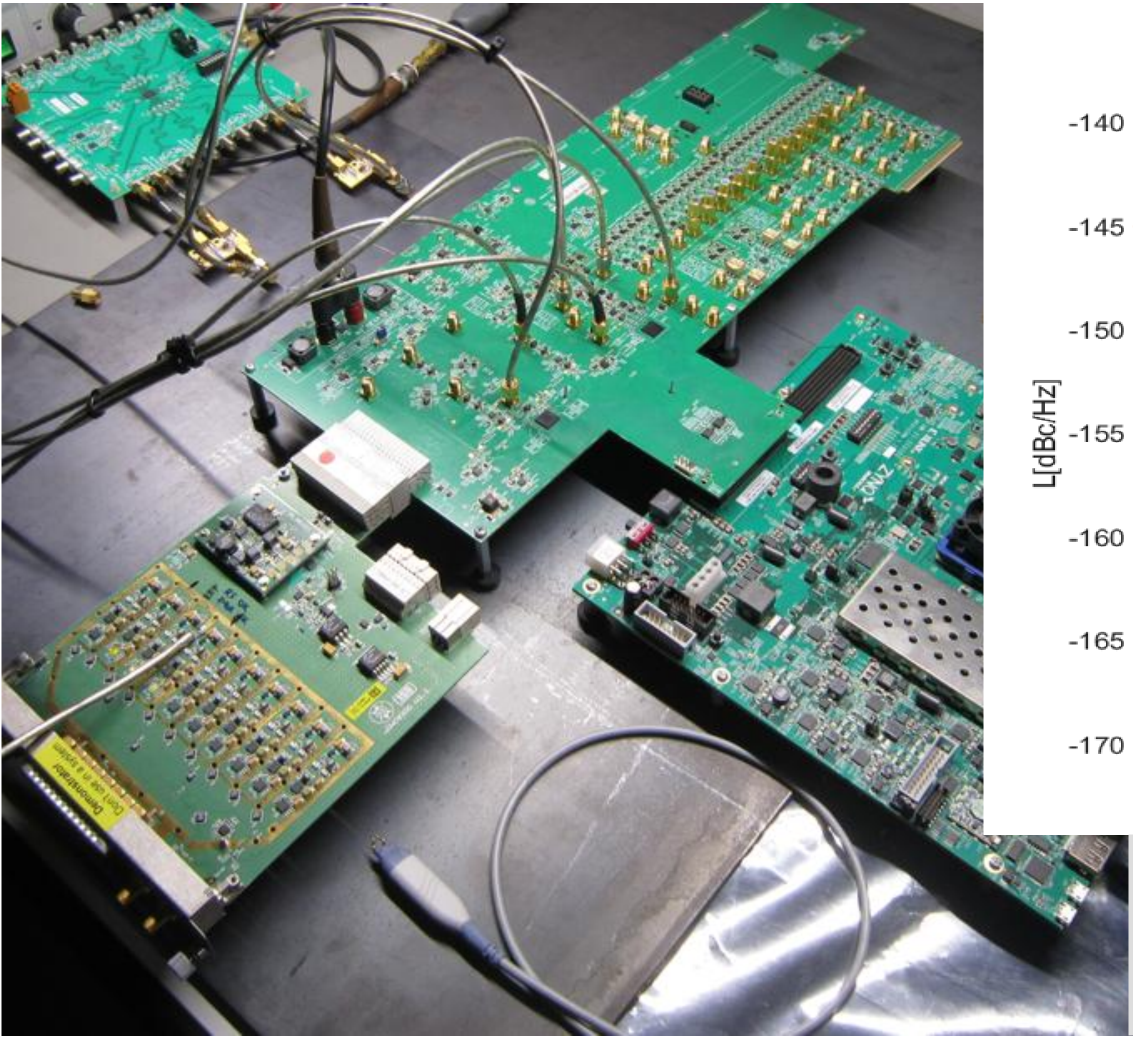




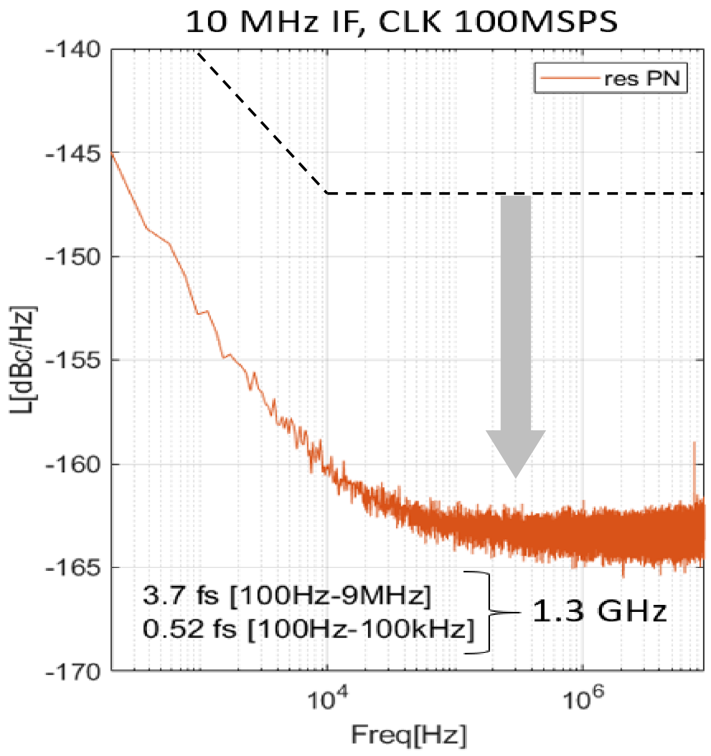
Next Generation – Field Detection – Non IQ Sampling (<1fs)

- Distributed heterodyne receiver in evaluation phase (2026):

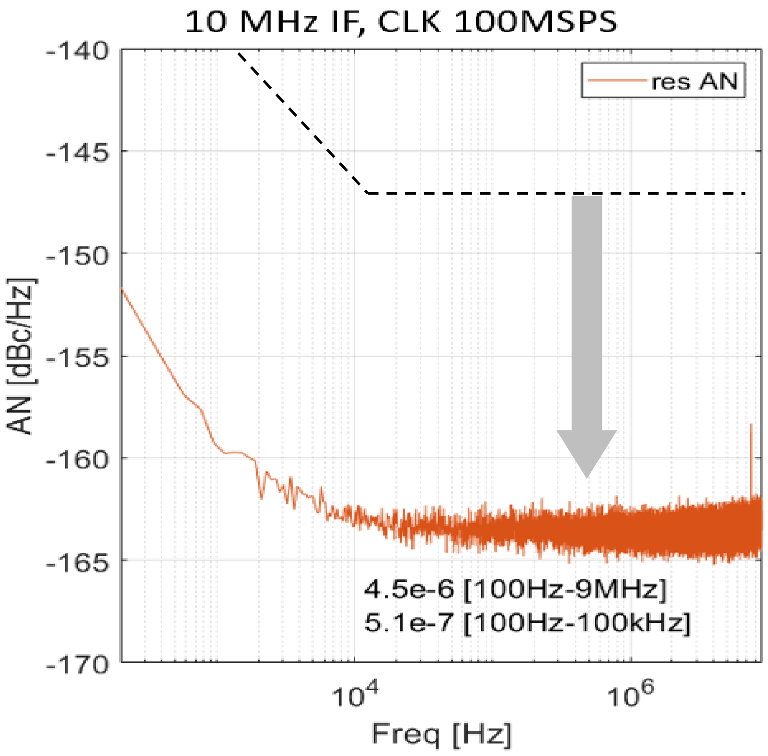
Courtesy of U.Mavric
Preliminary



Phase noise



Amplitude noise

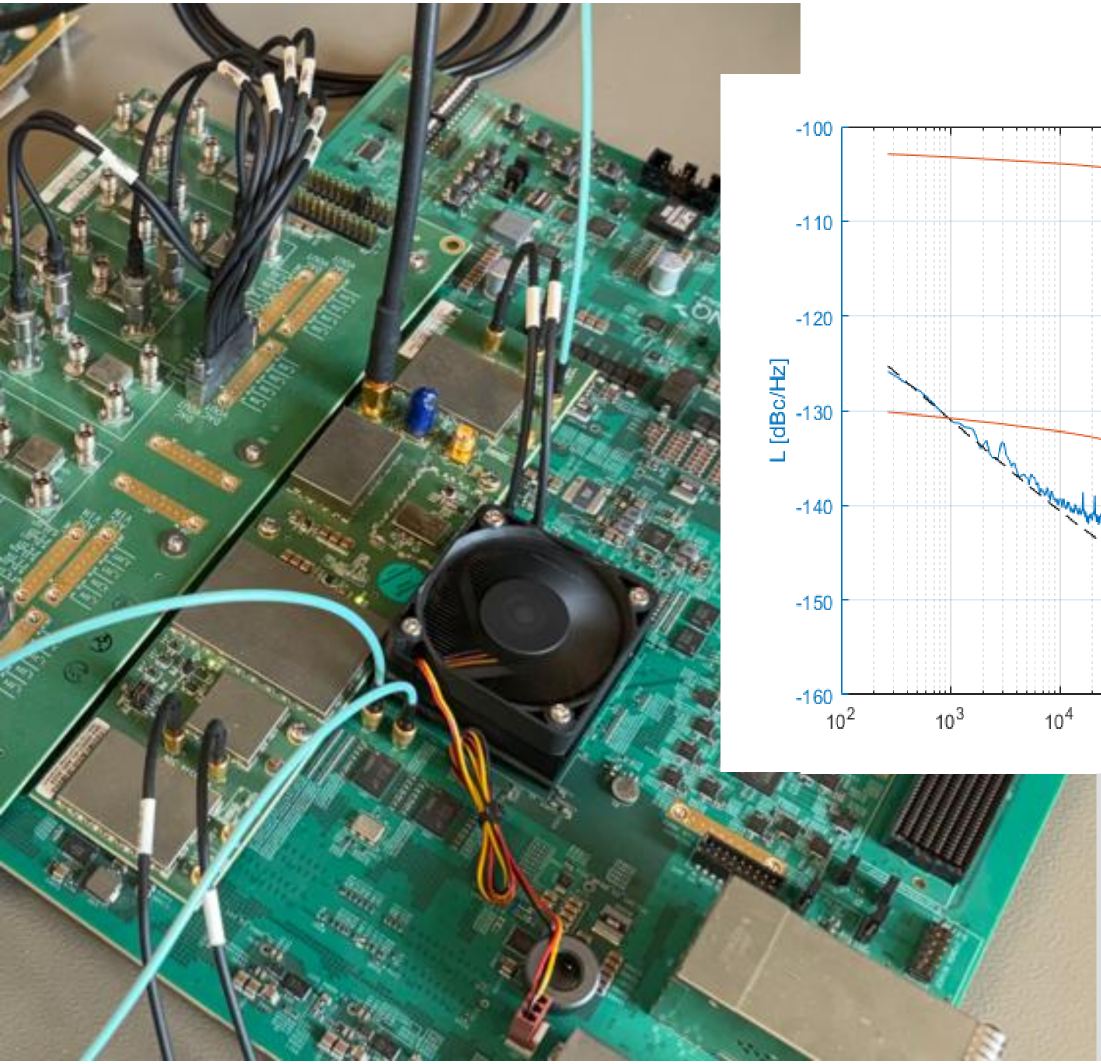


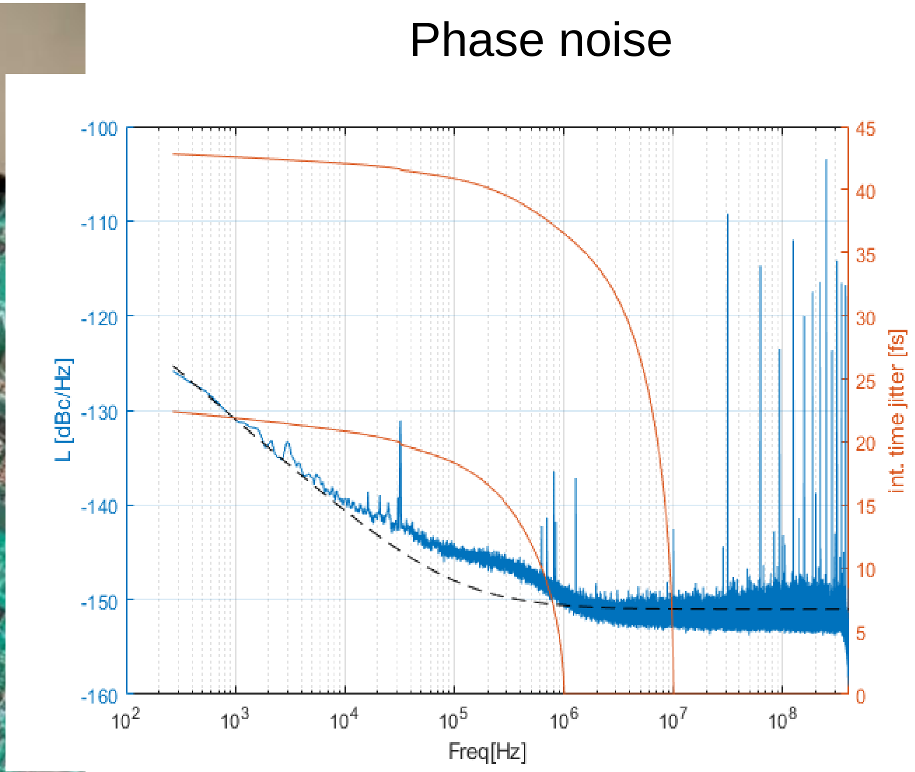
- Expected improvement by 16dB to 0.6 fs [100 Hz, 100 kHz]
- Packaging in MicroTCA.4 and spur removal is a challenge.

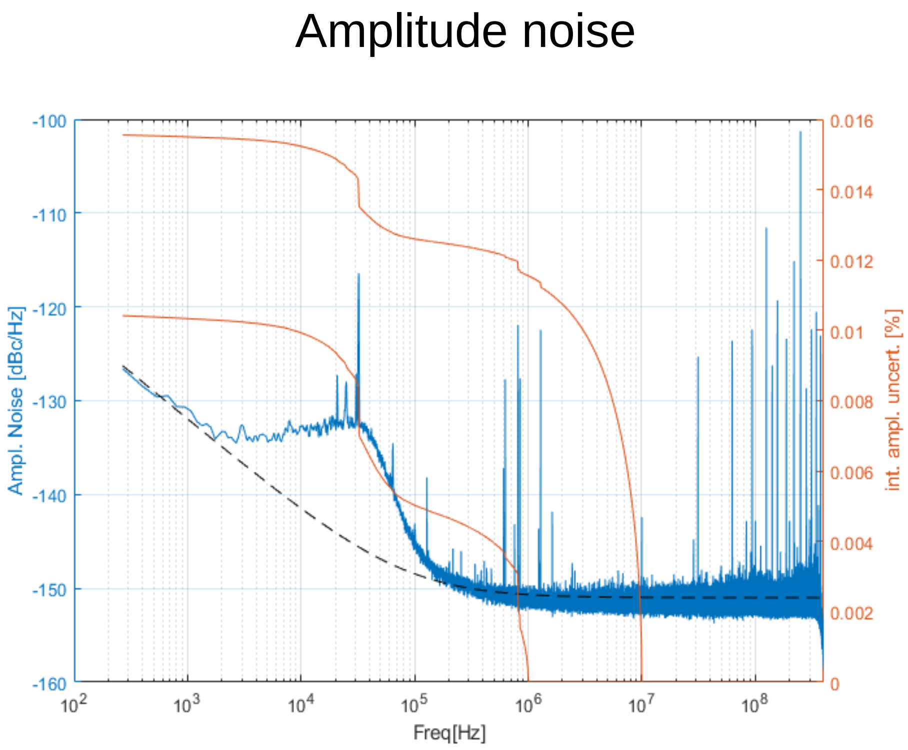
Next Generation – Field Detection – Direct Sampling (fast)

- Integrated receiver characterization and system integration (RFSOC 500MHz, 2.25Gsps):

Courtesy of
U.Mavric, B. Boghrati







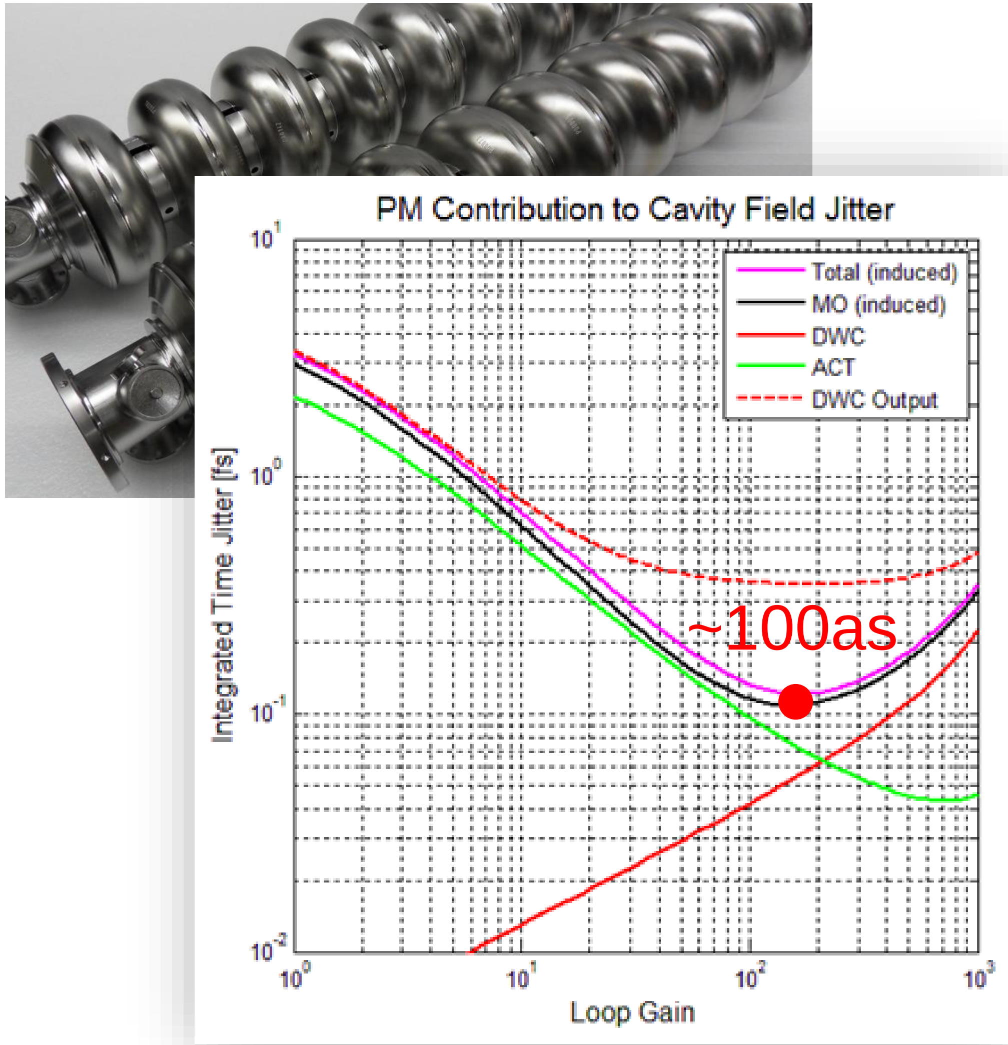
Promising results of the RFSOC coming up in many form factors:

- Bandwidth : 6GHz bandwidth for many LLRF systems
- Phase nosie : 22fs, 43fs (1MHz,10MHz BW)
- Amplitude noise : 0.01%, 0.016% (1MHz,10MHz BW)

RF-Controls with as-Precision

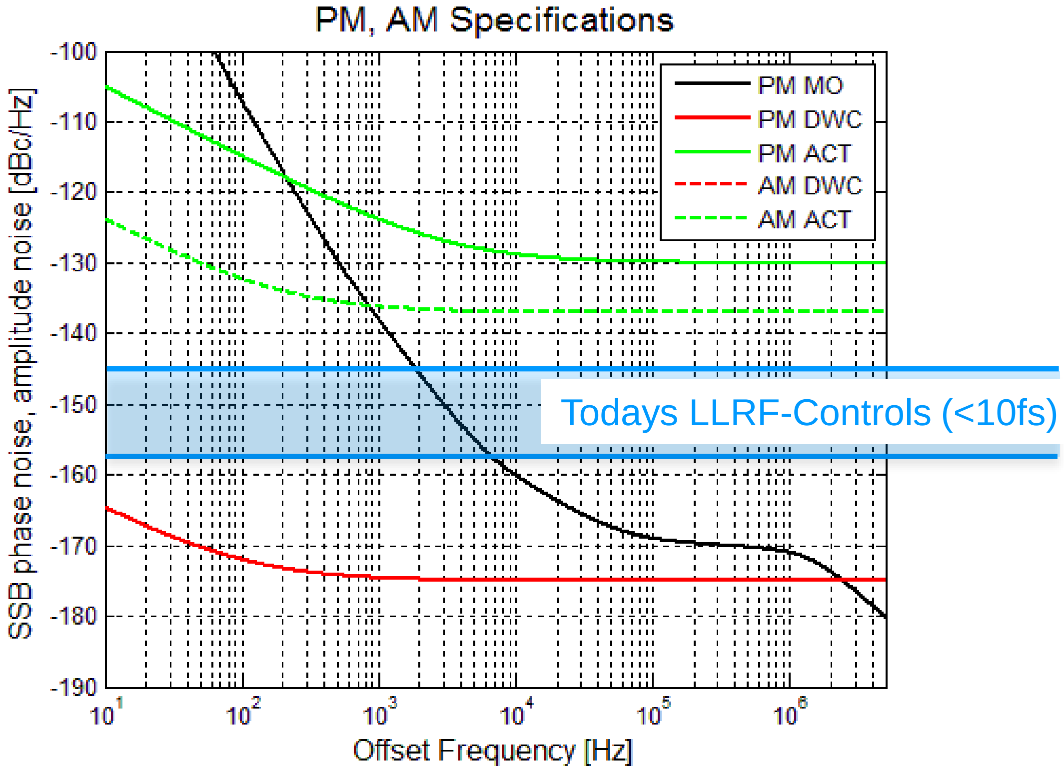
Towards as-Precision – LLRF Component Requirements

- SRF-Cavity (1.3GHz, Q_L $3{\cdot}10^6$, BW 200Hz) :



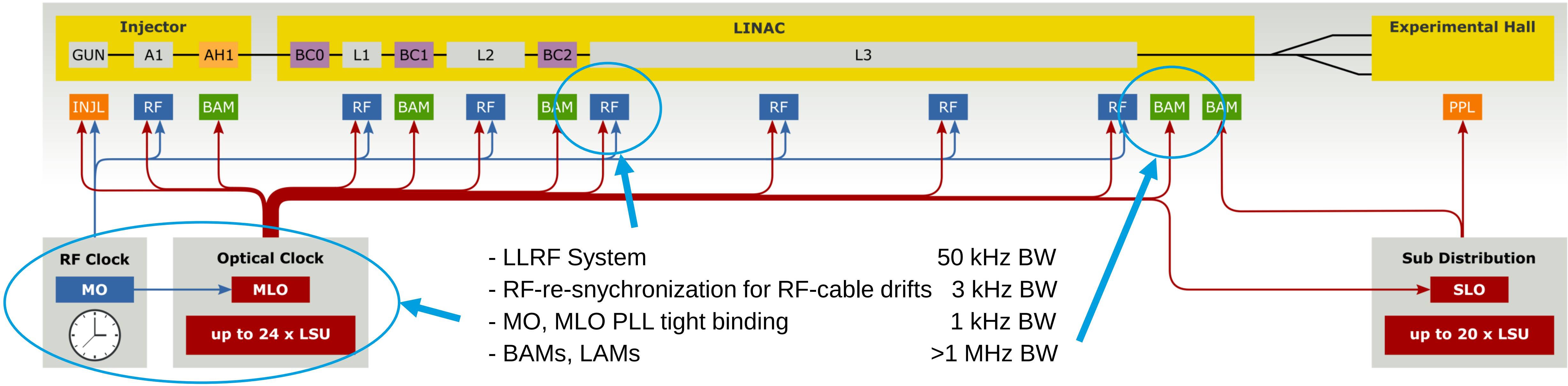
- LLRF Component Requirements :

Main reference (MO) : <-170dBc/Hz
Actuator chain (ACT) : <-140dBc/Hz
Field detectors (DWC) : <-175dBc/Hz (-150dBc/Hz)



Main-Oscillators – Why do we need excellent sources ?

- e.g. RF-synchronization in combination with an optical synchronization:



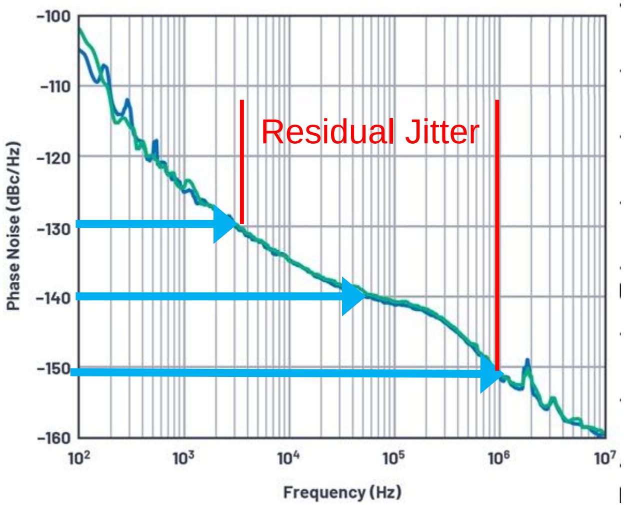
- LLRF System	50 kHz BW
- RF-re-synchronization for RF-cable drifts	3 kHz BW
- MO, MLO PLL tight binding	1 kHz BW
- BAMs, LAMs	>1 MHz BW

- Sub-systems have different noise BWs :

MO, MLO PLL
REFM-OPT

LLRF-System

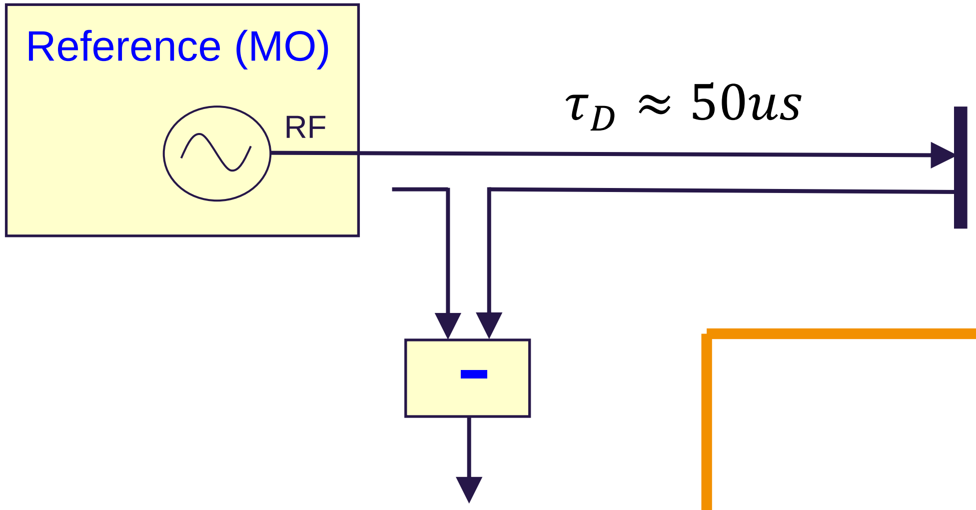
BAMs



- Low 1/f-noise Main-Oscillator
- Low noise MLO
- Relevant MO frequency range:
  Middle range [500Hz, 100kHz]

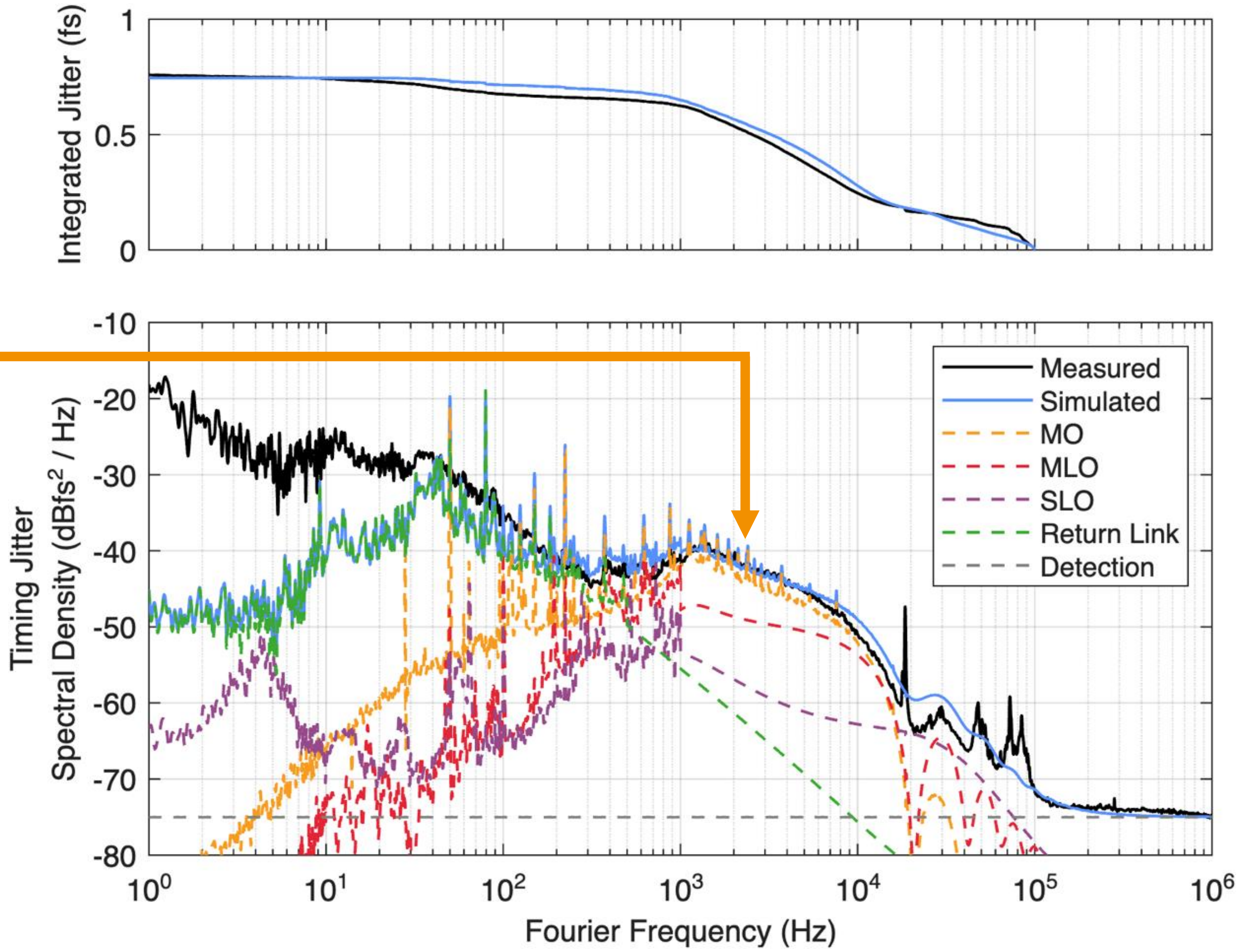
Advances in Main-Oscillators for Accelerators (<1fs) – Links

- Residual noise of 2 optical links (7km):
  (Simplified -> Discriminator)



$$S_{\varphi,RES}(f) = S_{\varphi,MO}(f)\, 4\, sin^2(\pi\, f\, \tau_D)$$

Courtesy of M.Schütte

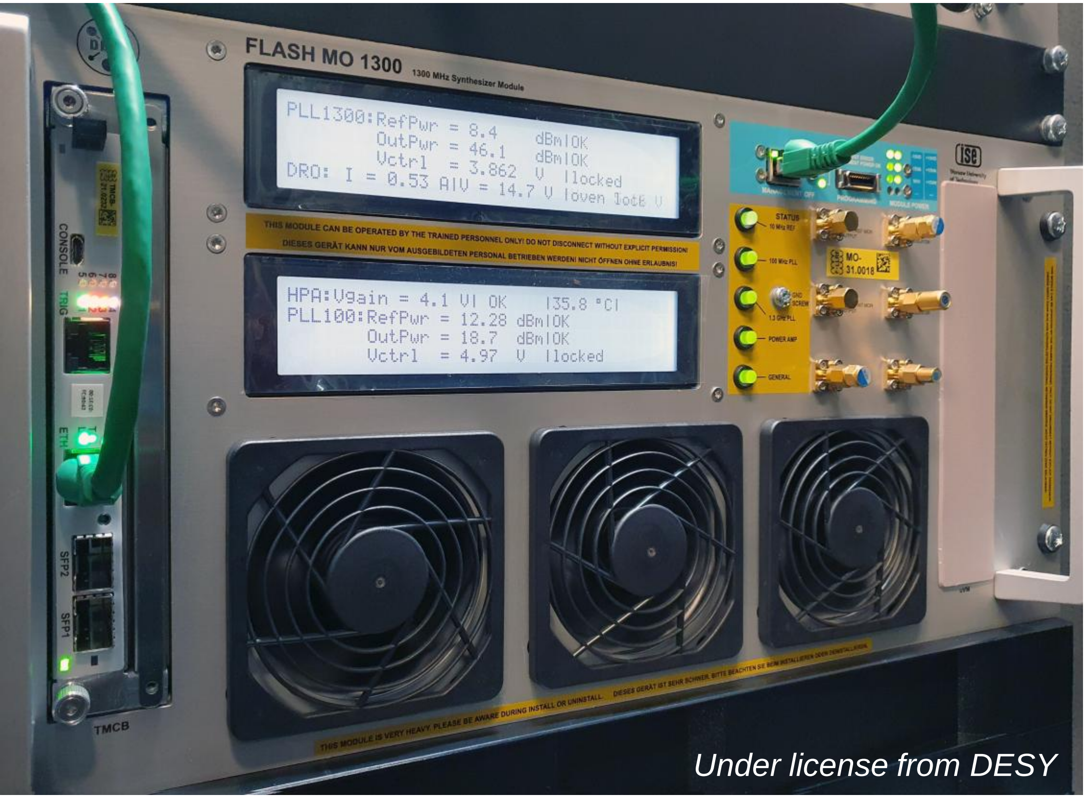


> Delays or long links require low phase noise from main references in the middle frequency range

Advances in Main-Oscillators for Accelerators (<1fs)

- XFEL, FLASH new Main Oscillators:

1.3GHz (3.0GHz), +46dBm, Health monitoring

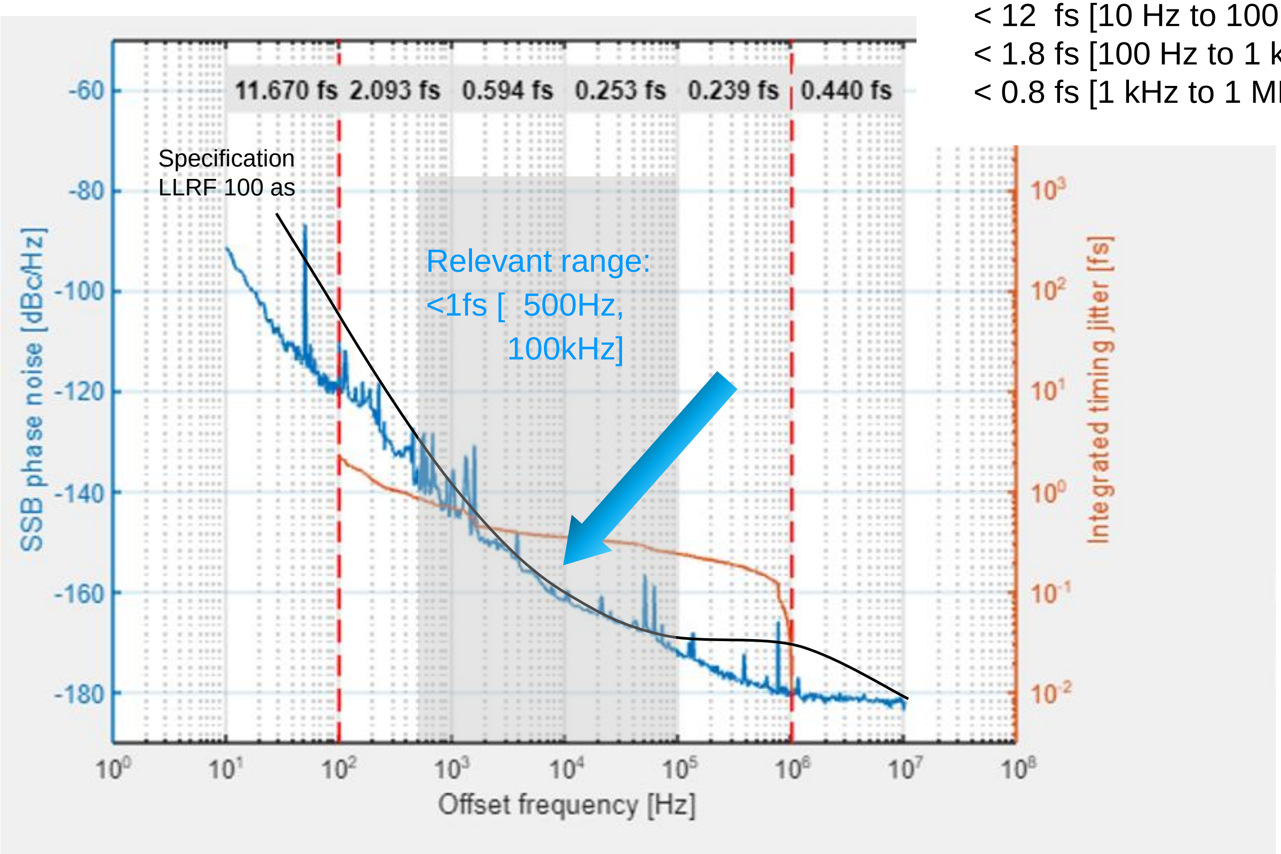


KVG Quartz Crystal Technology GmbH
info@kvg-gmbh.de

Quartz Crystal Technology GmbH

- Absolute Phase-noise:

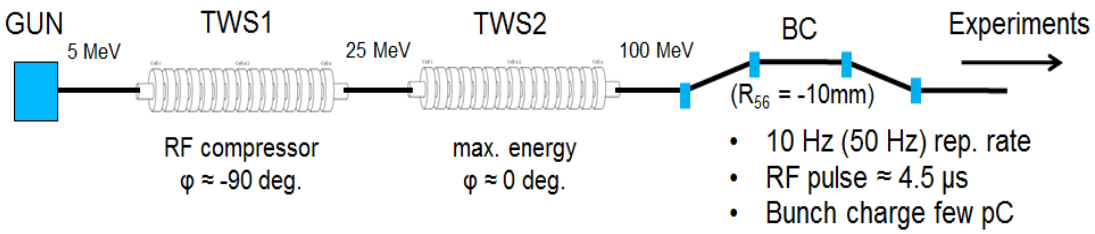
Integrated Jitter:
< 12 fs [10 Hz to 100 Hz]
< 1.8 fs [100 Hz to 1 kHz]
< 0.8 fs [1 kHz to 1 MHz]



- Improvement of int. jitter from 40 fs to 0.8 fs [1kHz, 1MHz]
- fs-lasers locking to reference show improvement to <150as

Advances in Actuators Klystrons (pulsed), SSPAs (CW)

- TWS Structure (3GHz, f_{12}=500kHz BW):



- VM+PA+KLY Stability (additive jitter):

-> MOD/KLY @850V (20ppm), 10MW

REGAE, XFEL TDS (PM, AM)

1. KLY MOD

1/f-noise : 13.79fs, ~0.049%, [min,1MHz]

2. Power Amplifier

1/f-noise : 3.4fs, ~0.0039%, [min,1MHz]

3. Vector-Modulator

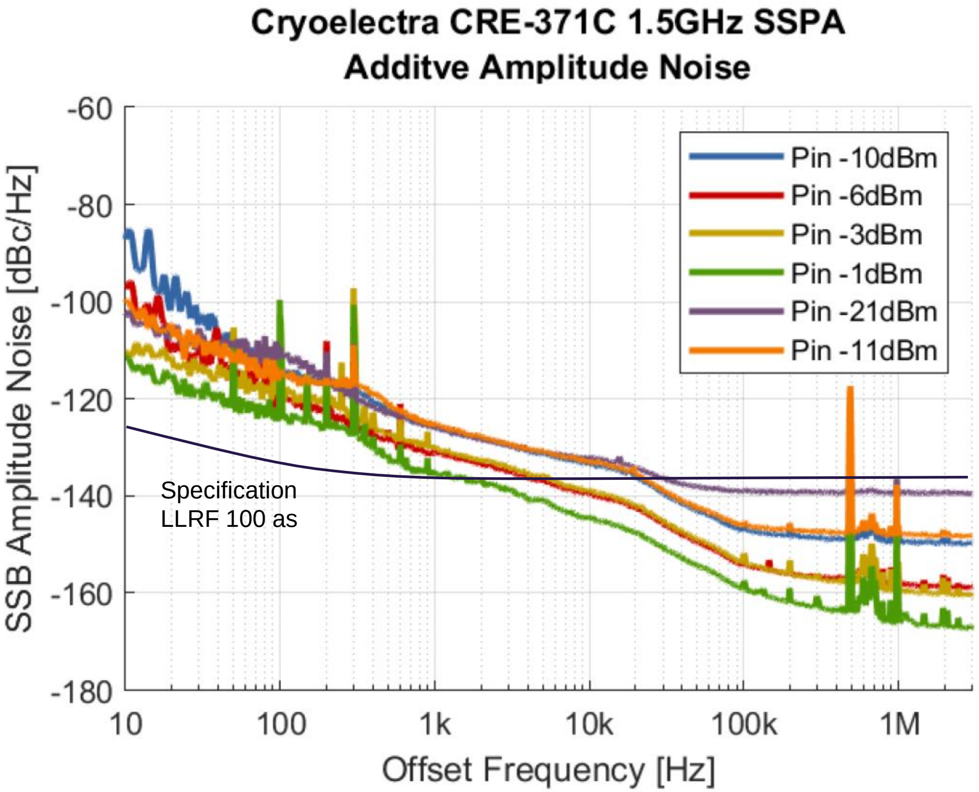
1/f-noise : 2.9fs, ~0.0063%, [min,1MHz]

High-power chain :

-> 14.5fs, 0.049%, -165dBc/Hz

-> Hidden middle f-range

- SSPA Stability (1.5GHz, 20kW):



Int. AN Jitter:
0.03% …
0.007%

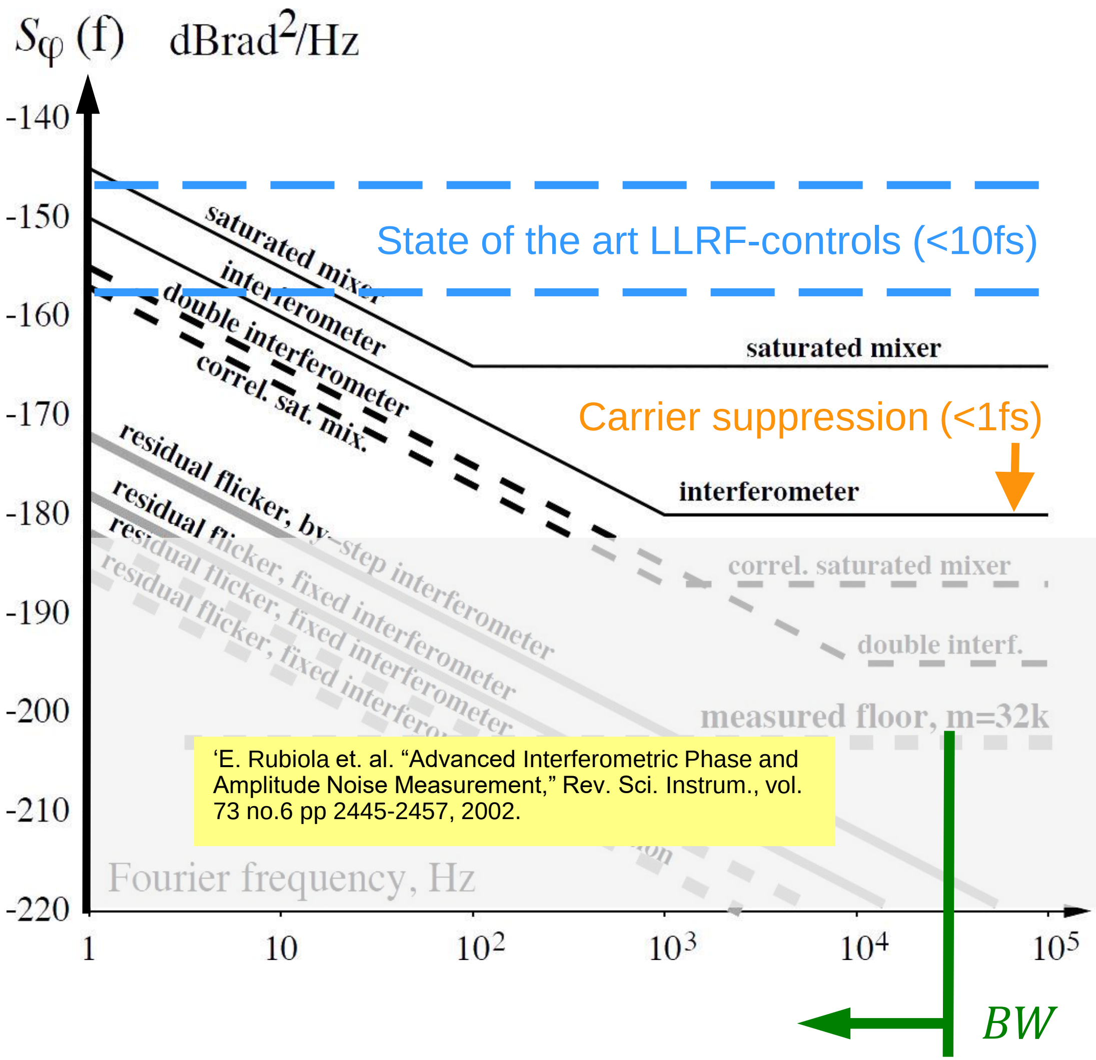
Integrated Jitter :

-> 8fs …30fs depends on spurs

-> 0.01%...0.03% depends on spurs & power level

Towards as-Precision – Options (Field Detection)

- Options to increase the measurement resolution <100as (real time):



'E. Rubiola et. al. "Advanced Interferometric Phase and Amplitude Noise Measurement," Rev. Sci. Instrum., vol. 73 no.6 pp 2445-2457, 2002.

① Increase the RF-power:
- PN, AN linear in RF-power
- High level mixer
- Carrier Suppression Interferometer

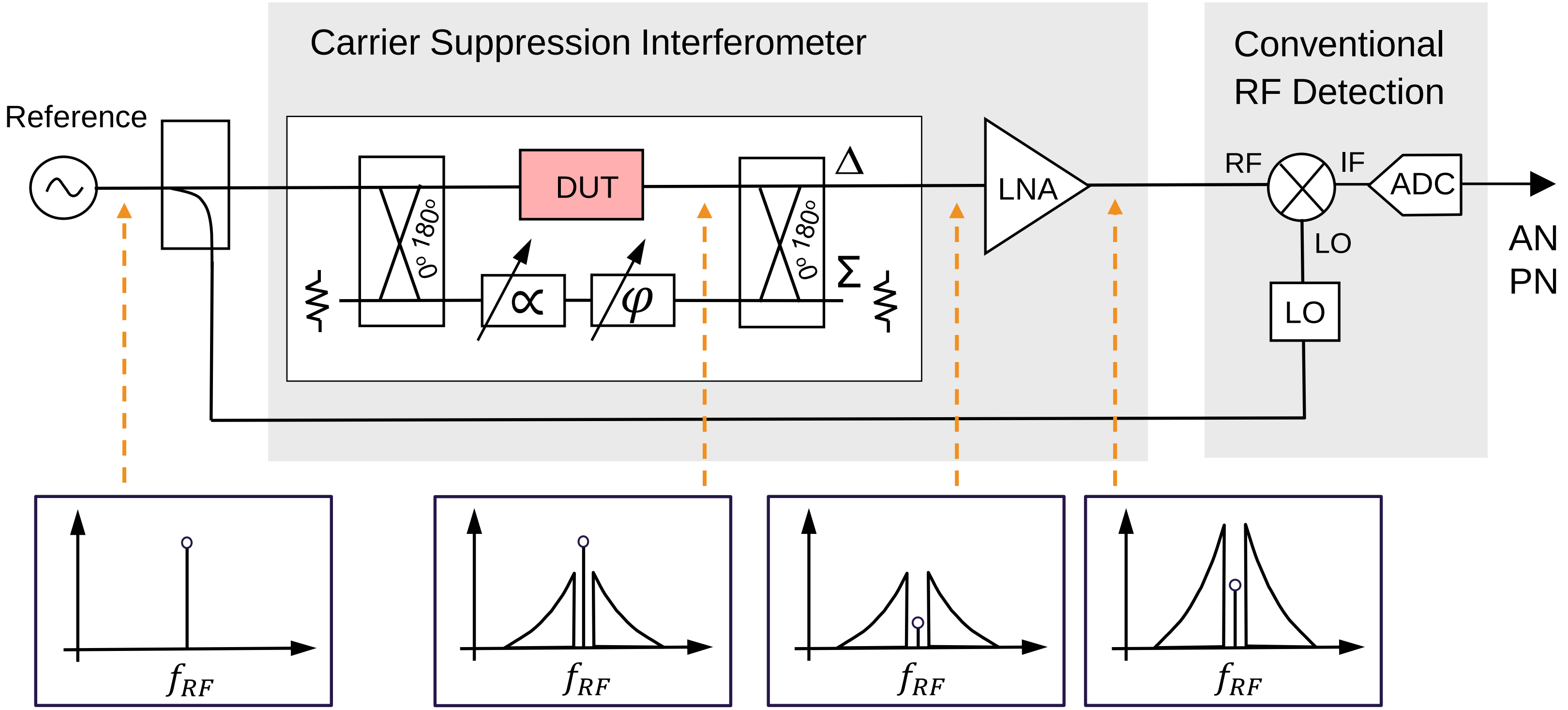
② Reduce the noise floor:
- ADC/Channel parallelization, ~\sqrt(N)
- ~~Time correlation (no real time)~~

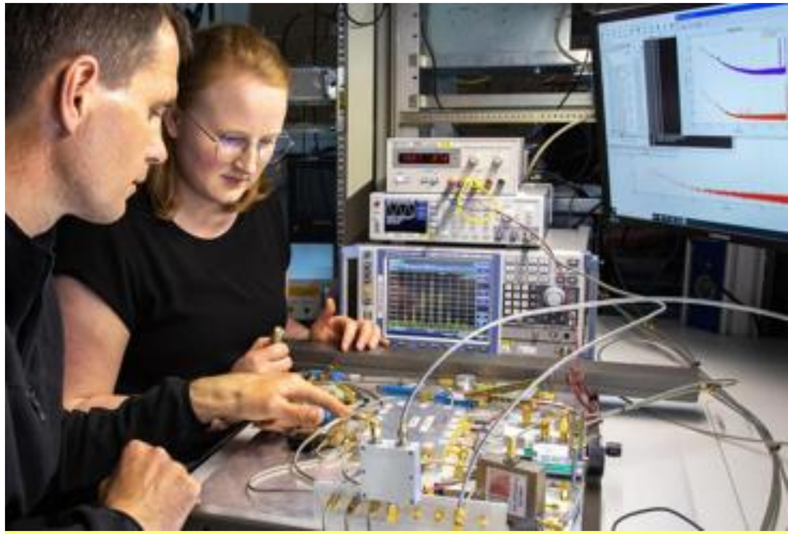
Correlation techniques

③ Reduce the cavity bandwidth:
- Use >16-bit ADCs with better NSD
- Microphonics increase

Advances in Field Detection with as-Precision (<100as) – CSI

- Carrier-Suppression-Interferometer for residual AN, PN measurements (simplified):





L. Springer *et al.*, "Phase Noise Measurements for L-Band Applications at Attosecond Resolution," in *IEEE TIM;*, doi: 10.1109/TIM.2022.3170975.

(+) No carrier -> no 1/f-noise from LNA, DUT noise pass the system

(+) PN, AN scales with RF-power

(--) Needs a carrier tracking for destructive interference

Resolution 10as (realtime) :

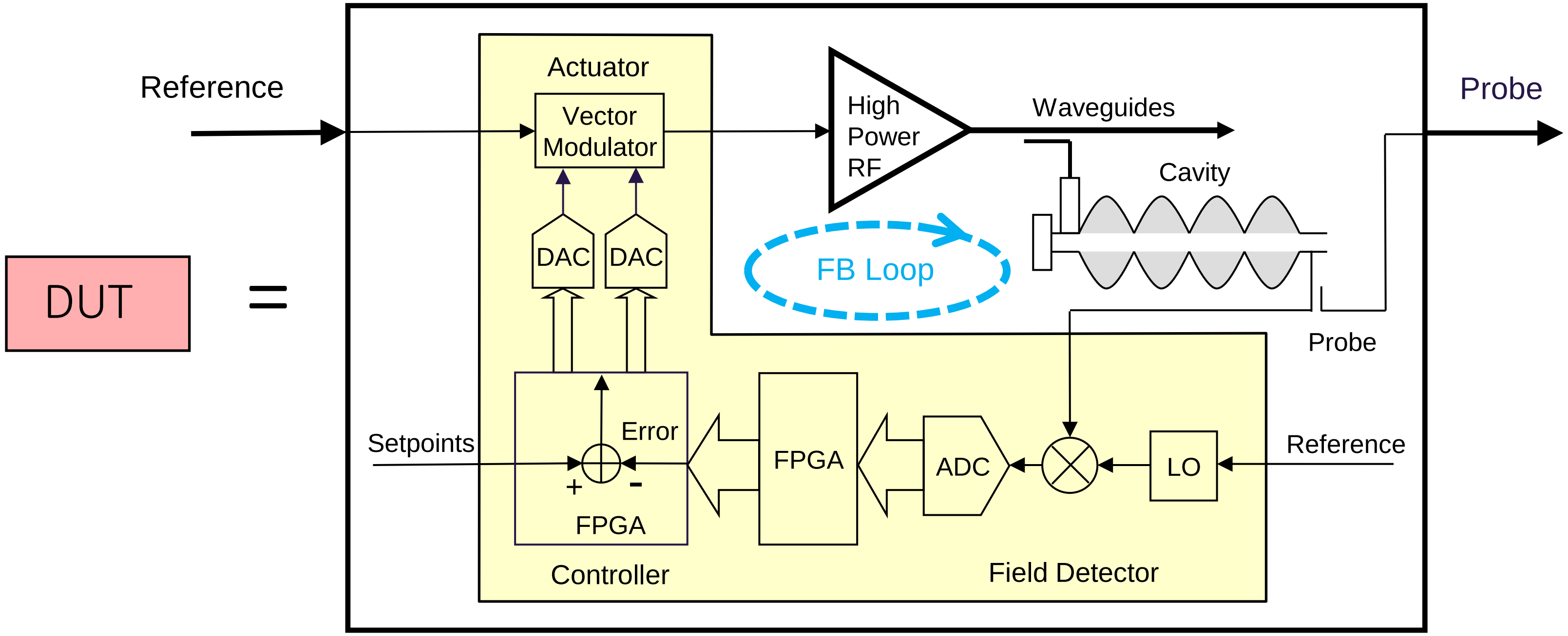
(+) PN, AN <-205dBc/Hz, @1.3GHz jitter

(+) Low 1/f-noise -180 dBc/Hz @ 100Hz

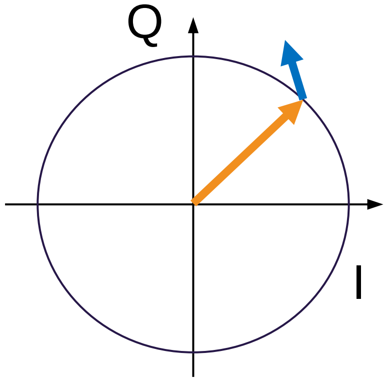
↷ How to use this for RF control in accelerators ?

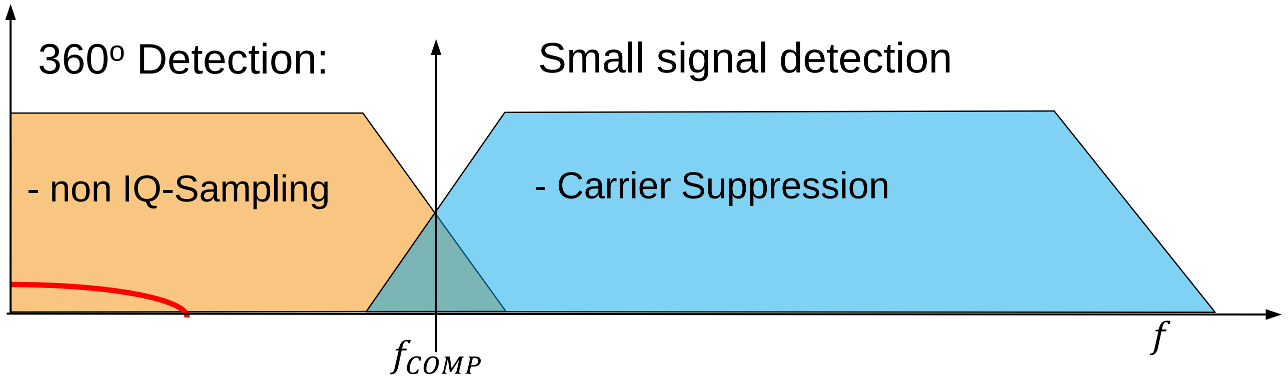
Advances in Field Detection with as-Precision – CSI

- Replacement of the DUT as the complete RF Control: (for AN slightly different)



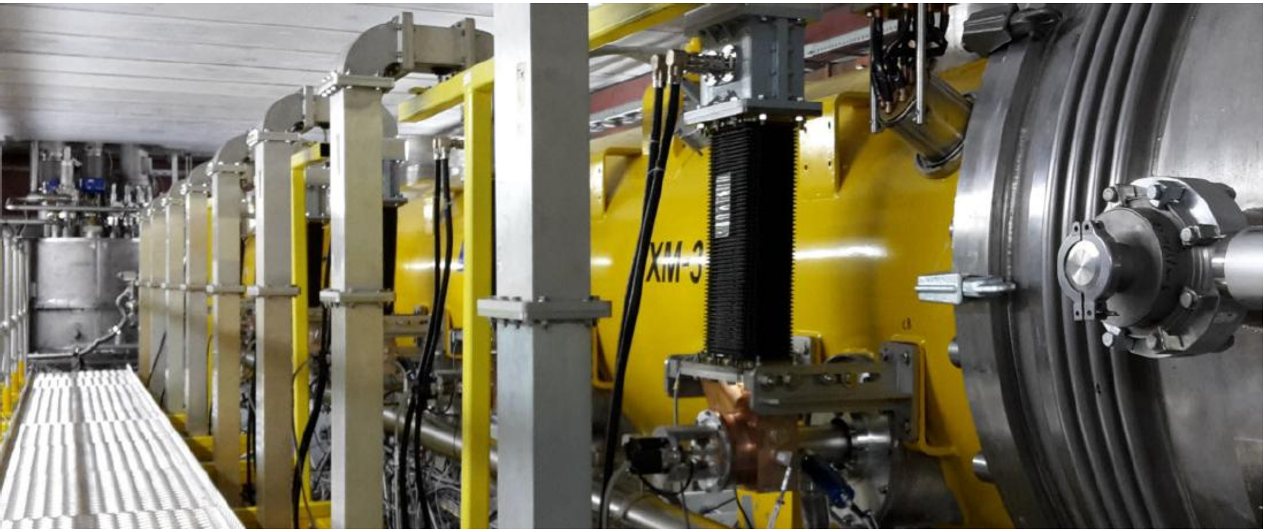
- Large signal detection - Hybrid with non-IQ: e.g. CW-operation



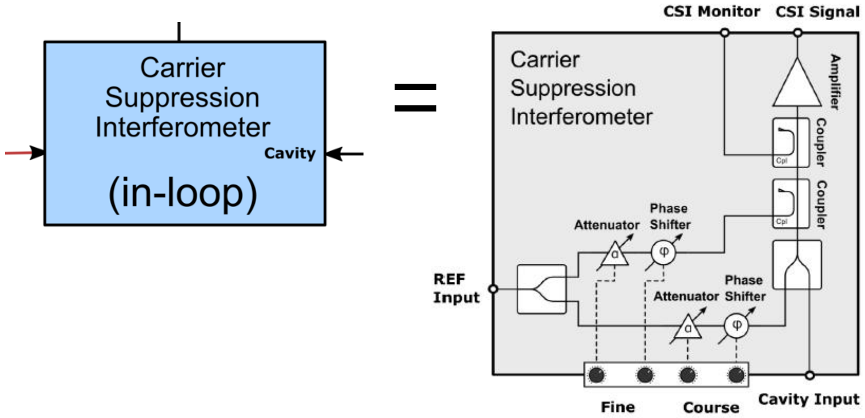


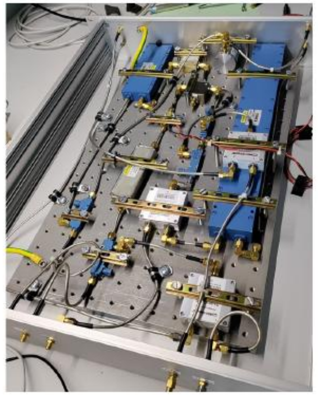
Advances in Field Reguation with as-Precision – CMTB

- Cryo-Module-Test-Stand (CMTB) @ DESY:

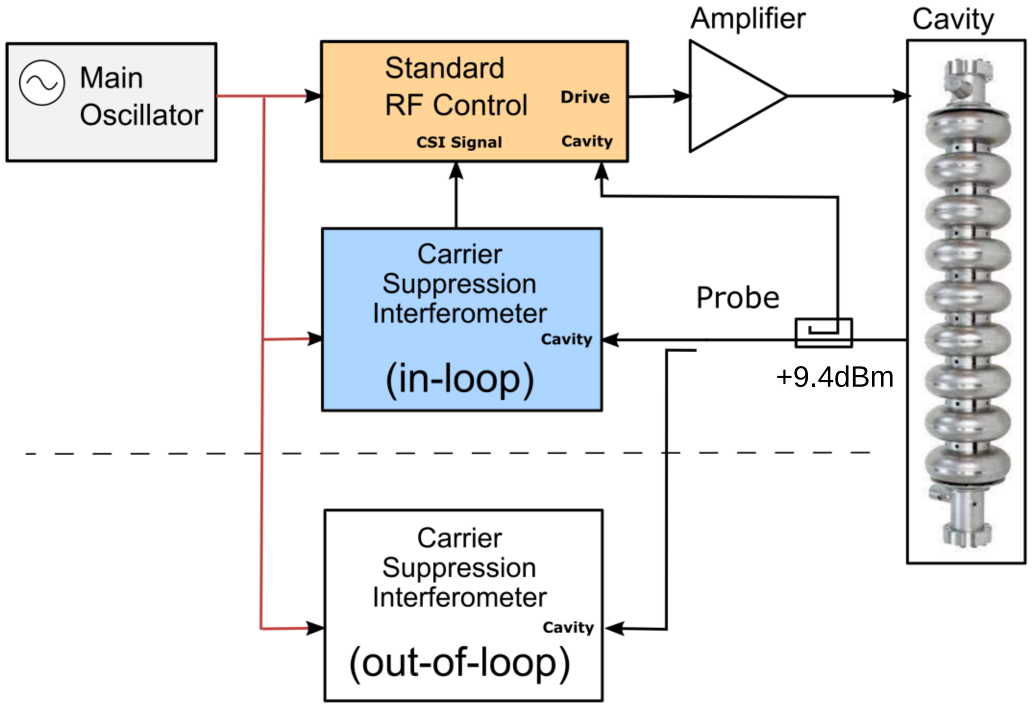


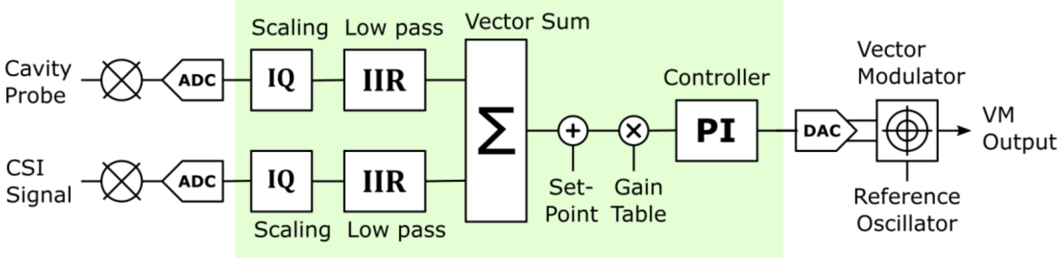
SRF 1.3 GHz, BW 65 Hz, $Q_L=10^7$ at 8MV/m, IOT Amplifier, ANC off





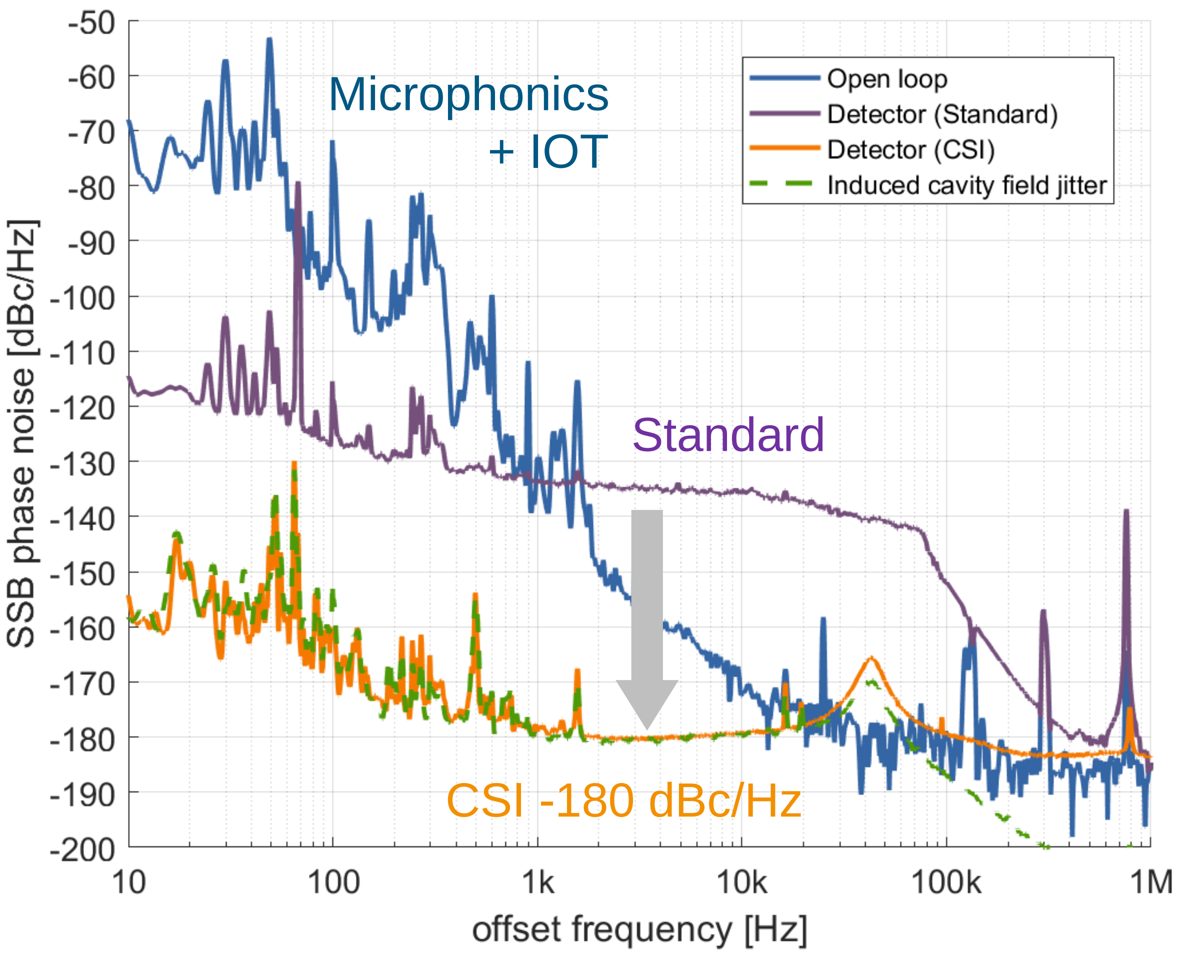
- Hybrid system of a MicroTCA.4 LLRF system and a Carrier-Suppression Interferometer:





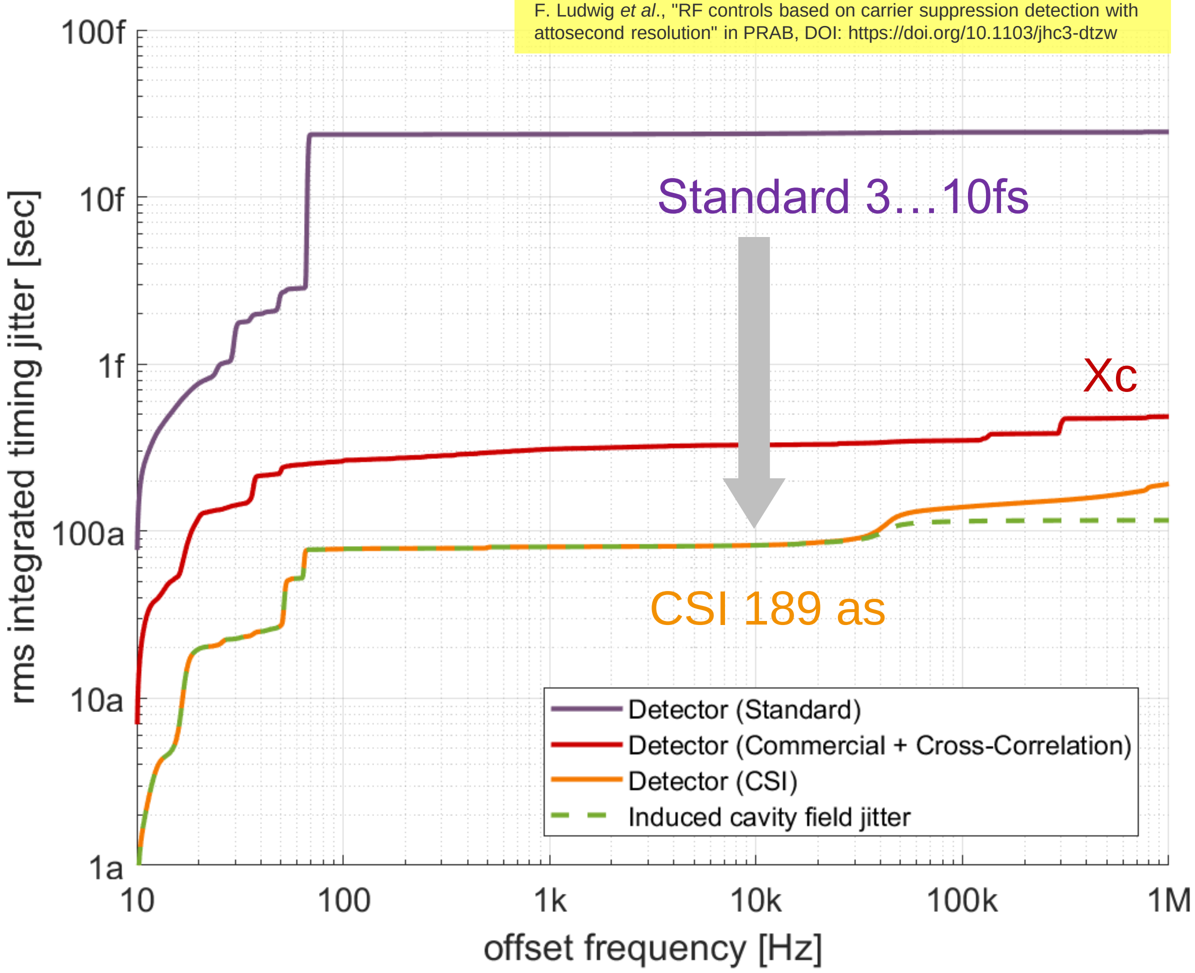
Advances in Field Regulation with as-Precision – CMTB

- Phase noise measurements (out-of-loop):



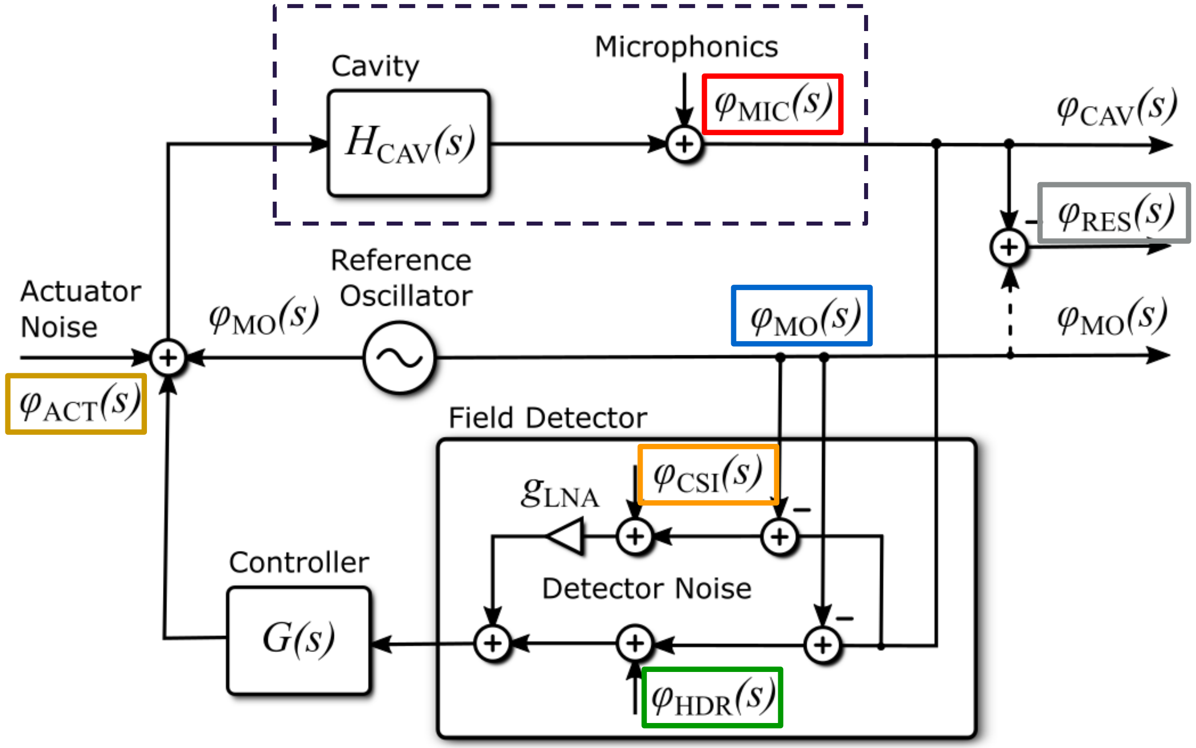
- Integrated time jitter (out-of-loop):

F. Ludwig *et al.*, "RF controls based on carrier suppression detection with attosecond resolution" in PRAB, DOI: https://doi.org/10.1103/jhc3-dtzw

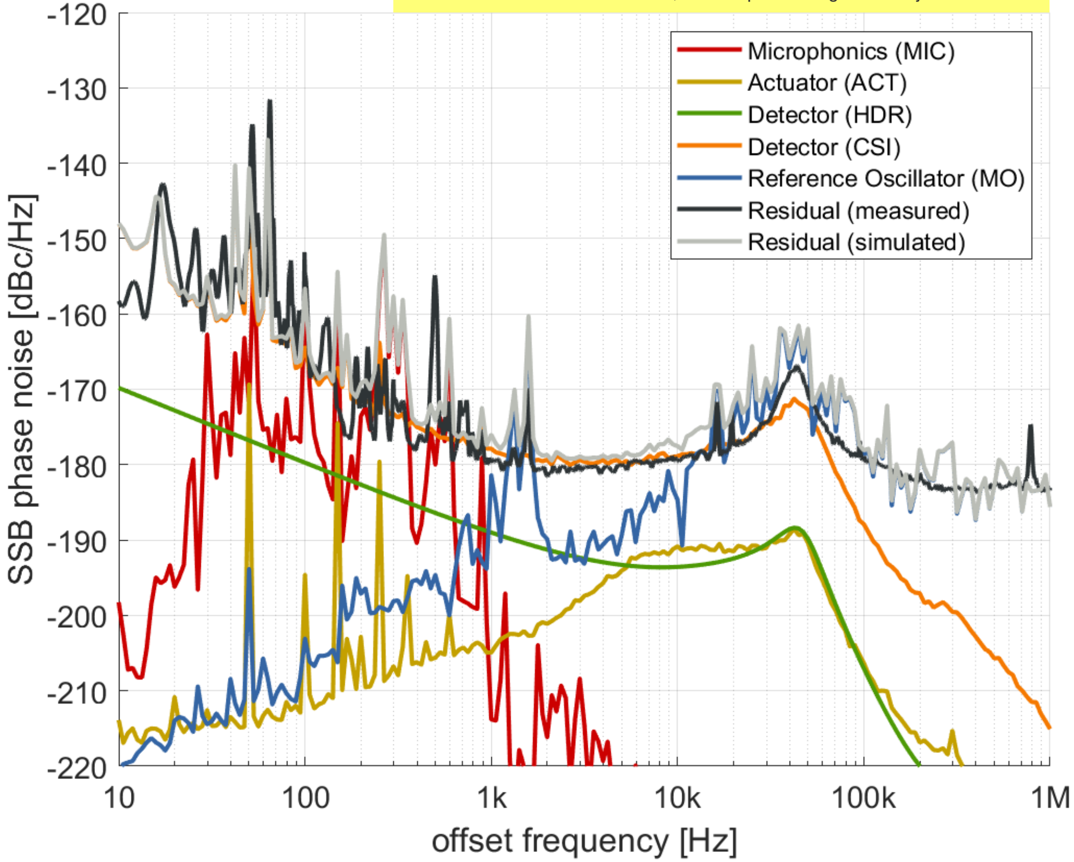


Advances in Field Regulation with as-Precision – Modelling

- Numerical simulation of the LLRF system:



F. Ludwig *et al.*, "RF controls based on carrier suppression detection with attosecond resolution" in PRAB, DOI: https://doi.org/10.1103/jhc3-dtzw



$$S_{\varphi,RES,i}(f) = |K_i(f)|^2 \, S_{\varphi,i}(f)$$

- Determine all noise transfer functions from the modell
- Measure each noise source individual
- Determine all noise contributions and total residual noise

↝ - Measurements and simulations fits quite well.
- Reference, Actuator, Microphonics are suppressed.
- Cavity RF-power limits the CSI.

Advances in Field Detection with as-Precision – Challenges

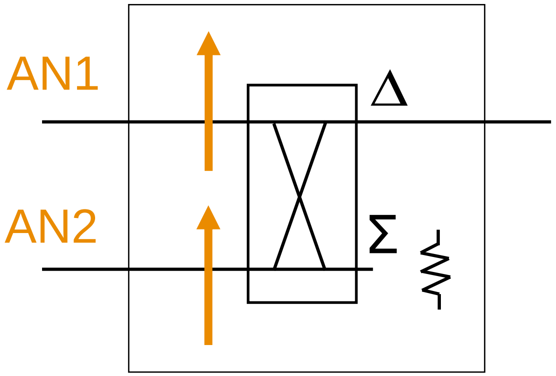
- Fundamental difference in closed-loop amplitude behavior:

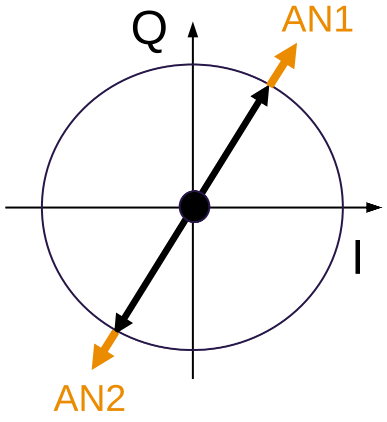
  - Cavity field phase is relative to the reference.
  - Cavity field ampltitude is absolute.

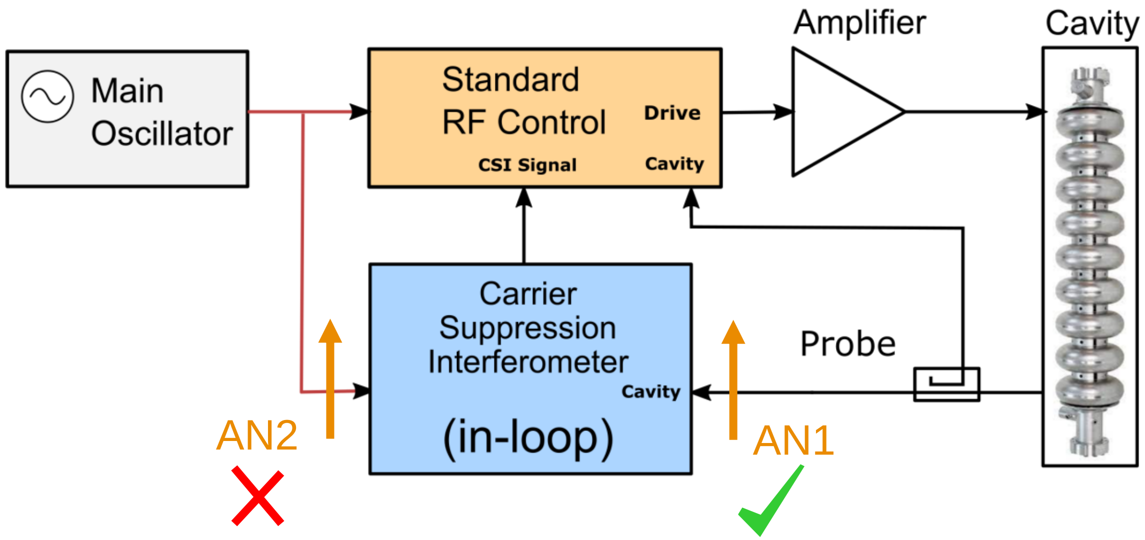
Amplitude **Phase** **Init. arrival**

$$t_{j,\mathrm{out}}^2 \approx \left(\frac{R_{56}}{c_0}\frac{\sigma_A}{A}\right)^2 + \left(\frac{C-1}{C}\right)^2\left(\frac{\sigma_\varphi}{c_0 k_{\mathrm{rf}}}\right)^2 + \left(\frac{1}{C}\right)^2 t_{j,\mathrm{in}}^2$$

- CSI Detector: Amplitude difference:







- The cavity field follows the phase **and** amplitude of the reference for the CSI detector..
- The amplitude noise of reference ocialltors needs to be improved far below -180 dBc/Hz.

FIL

Summary and Outlook

- RF-Controls with spurious free short-term amplitude and phase detection below <10fs [1MHz BW] is available for the accelerator community in modern standards like MicroTCA.4 or proprietary systems.

- RF-Controls with <1fs field stability is currently in preparation.

- RF-controls with <200as field stability is demonstrated in phase.

  To achieve amplitude stability at this level, the main references must be improved.

Thanks for your attention!

Backup

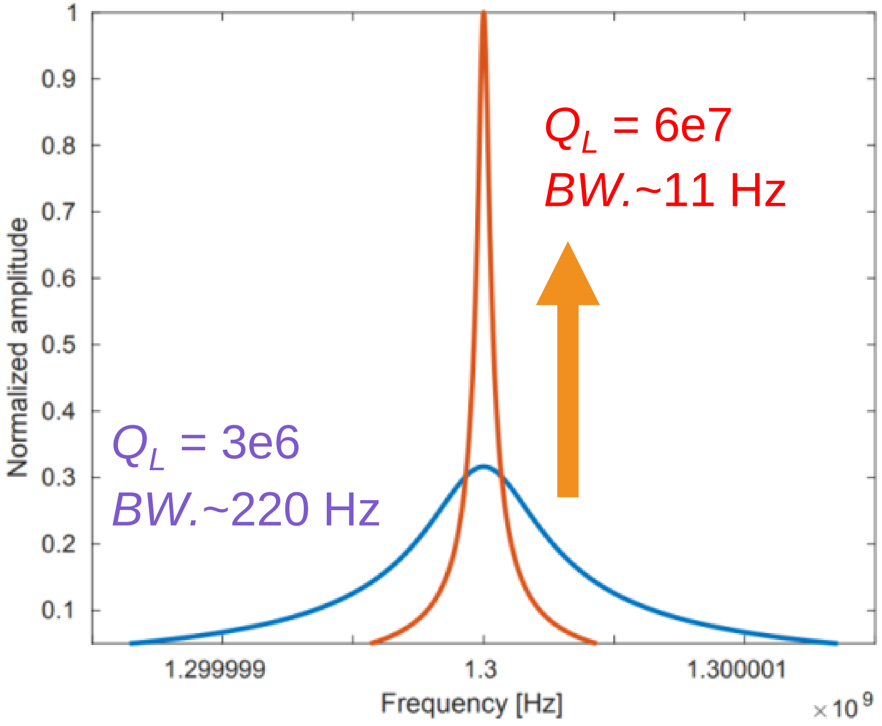
High-Q_L Cavity Operation – CW Operation

- Increasing the cavity external quality factor:

  (+) Less power required to achieve same gradient

  (+) Reduced effective noise bandwidth

  (--) More sensitive to microphonics

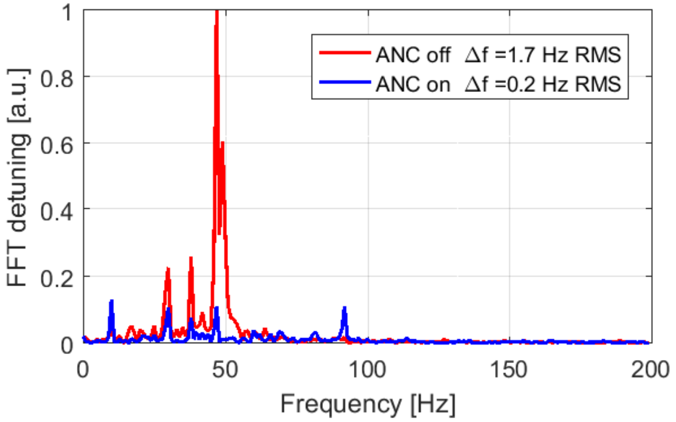


- Suppress microphonics:

  - Apply Active Noise Cancellation to notch measured frequencies

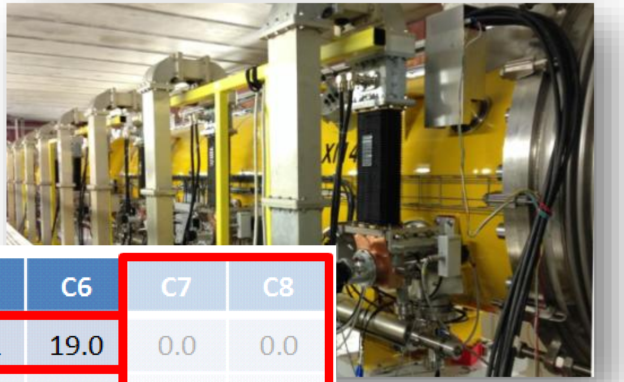
  - Suppression > 20 dB can be achieved

“FPGA-Based RF and Piezo controllers for SRF Cavities in CW Mode”, R. Rybaniec et al. IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 64, NO. 6, JUNE 2017



- Results for high Q_L, high gradient, vector-sum :

  - CW operation in vector sum
  - using piezo and RF feedbacks



	C1	C2	C3	C4	C5	C6	C7	C8
Eacc [MV/m]	20.0	20.5	20.3	20.6	20.1	19.0	0.0	0.0
QL [x1e7]	6.2	6.2	6.3	6.1	6.1	6.2	2.8	2.8

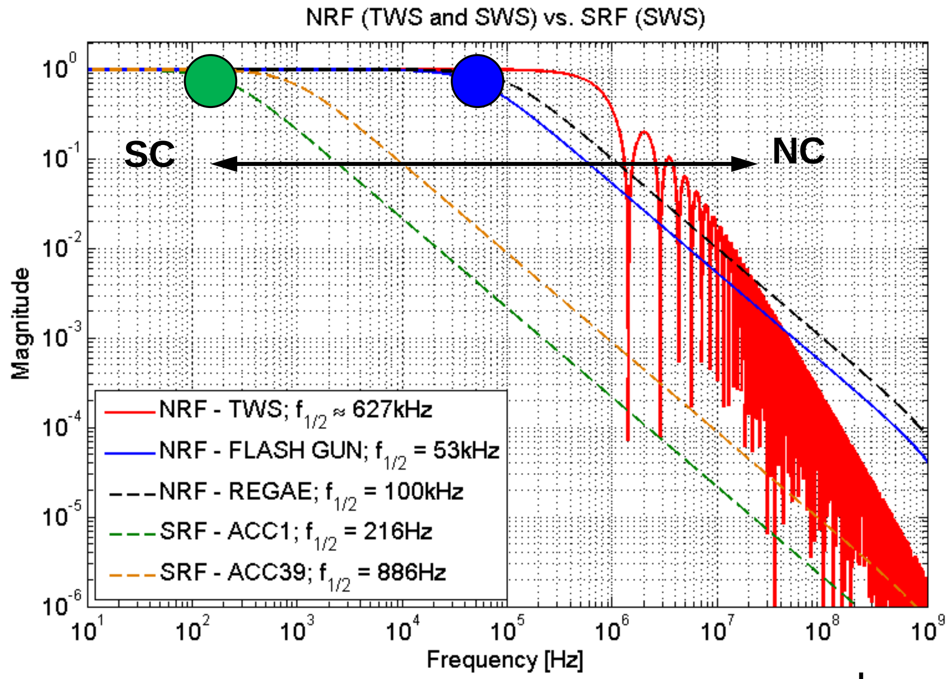
dA/A ~ 0.007%, dP ~ 0.015 deg.

Excluded from VS due to Ql max < 6e6

Courtesy of J.Branlard

Noise Contributions – SRF vs. NRF

- Minimal residual noise contribution (very simplified, no 1/f-noise, no spurs):

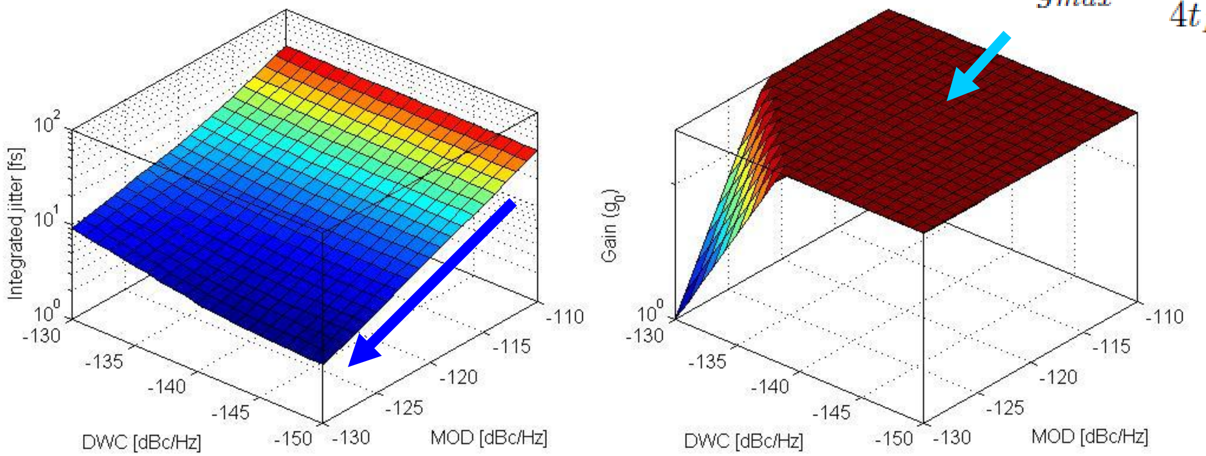


$$g_{opt} = \sqrt{\frac{S_{\varphi,0,\mathrm{ACT}}}{S_{\varphi,0,\mathrm{DWC}}}} \qquad g_{max} = \frac{1}{4 t_D f_{12}}$$

$$\Delta\phi^2_{\mathrm{RMS}} = \left(g_0 S_{\varphi,0,\mathrm{DWC}} + \frac{1}{g_0} S_{\varphi,0,\mathrm{ACT}} \right) \frac{\pi}{2} f_{12}$$

NC-Cavity (f_c=3GHz, f_{12}=60kHz, t_D=1us Latency) :

$$g_{max} = \frac{1}{4 t_D f_{12}}$$



SC-Cavity (f_c=1.3GHz, f_{12}=216Hz, t_D=1us Latency) :